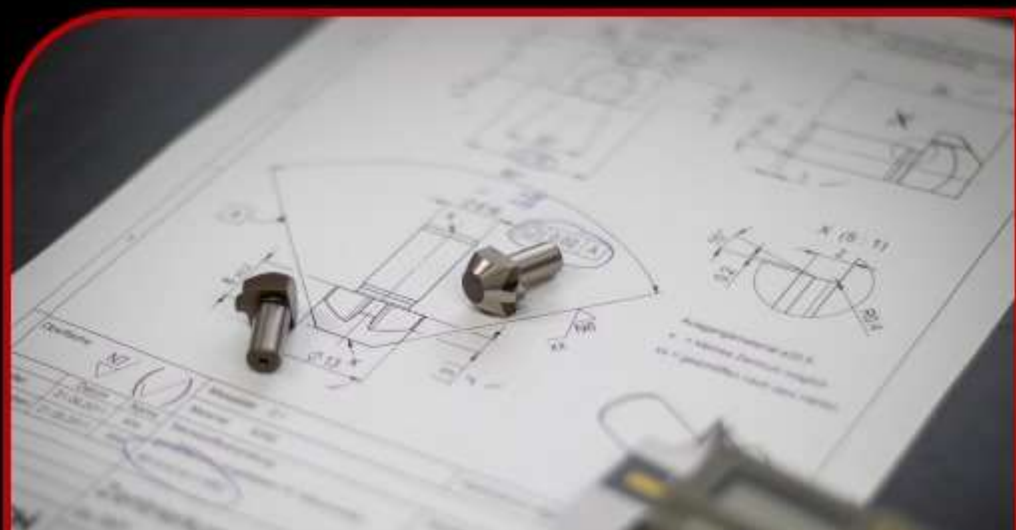
CURRENT CONCEPTS AND INNOVATIVE RESEARCH IN MECHANICAL ENGINEERING



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CURRENT CONCEPTS AND INNOVATIVE RESEARCH IN MECHANICAL ENGINEERING

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Prof. Dr. İSMET SEZER

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CONTENT

Enhancement Of Pool Boiling Heat Transfer On Coated Surfaces

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ABSTRACT

This section explains the surface modification methods used in pool boiling heat transfer and discusses how these alterations affect the heat transfer coefficient (HTC) and critical heat flux (CHF). Since the performance of conventional flat surfaces is limited by bubble clogging and insufficient liquid replenishment, micro/nano-scale surface structures provide significant enhancements in boiling.

Surface modification techniques are examined in two categories: physical and chemical. Physical methods (thermal spraying, PVD, laser texturing, etc.) improve bubble nucleation by altering the surface topography, while chemical methods (electrodeposition, anodization, CVD, sol–gel, etc.) enhance capillary liquid supply by controlling surface energy and wettability. Multi-scale hybrid surfaces, which combine both effects, offer the greatest performance improvements.

The enhancement in heat transfer arises from the combined effects of increased nucleation site density, improved wettability, porosity, capillary action, and enlarged surface area. The literature reports substantial increases in HTC and order-of-magnitude improvements in CHF with hybrid structures. However, coating durability and long-term stability remain important limitations that must be considered during the design process. Overall, surface modification is a powerful passive method to enhance pool boiling performance, offering the potential for safe and efficient operation at higher heat fluxes.

Keywords – Surface modification methods, surface coating, heat transfer coefficient, critical heat flux

INTRODUCTION

Boiling, as a phase-change heat transfer process, is widely used in industry due to its high heat transfer efficiency and large heat flux capacity. However, one of the most critical limiting factors in these applications is the heat transfer coefficient (HTC) and critical heat flux (CHF) associated with the heating surface (Liang et al., 2019:893). When a certain heat flux threshold is exceeded on conventional flat, polished, or standardized surfaces, adverse phenomena such as “dry patches,” insufficient liquid supply, and vapor blockage may occur on the heating surface. Under these conditions, heat transfer can deteriorate, system efficiency may decline, and in severe cases, the system may be damaged.

This fundamental problem has driven extensive research into achieving higher heat fluxes while maintaining reliability, efficiency, and surface stability. In this context, controlling the properties related to the modification of the heating surface -including its micro/nano-scale topography, chemical composition, porosity, and wettability- offers significant potential for enhancing both HTC and CHF in pool boiling (Chu vd., 2022:1).

SURFACE MODIFICATION METHODS

One of the most effective strategies for enhancing heat transfer in pool boiling applications is to modify the heating surface using physical or chemical techniques. Studies in the literature demonstrate that controlling surface topography, wettability characteristics, micro/nano structures, and chemical composition plays a decisive role in determining both HTC and CHF (Gilmore et al., 2018:1042). Within this context, surface modification methods can be broadly classified into two main categories: physical and chemical approaches

Physical Coating Methods

Physical modification techniques focus primarily on adjusting the micro/nano topography and geometric features of the surface without significantly altering its chemical composition. Surfaces produced through these methods typically enhance boiling performance by increasing the density of bubble nucleation sites and facilitating liquid supply. This improvement is achieved through controlled roughness, porosity, and cavity structures that promote more efficient vapor formation and fluid replenishment.

Thermal spray coating method

Thermal spraying techniques such as plasma spray, supersonic (HVOF) spray (700–1000 m/s), and cold spray deposit metal or ceramic powders onto a surface at high temperature and/or high velocity (Figure 1). The resulting coatings typically exhibit high roughness and pronounced porosity. These features increase the number of bubble nucleation sites and enhance the surface's capillary wicking capability. However, excessive coating thickness may introduce additional thermal resistance on the surface, which can partially offset the thermal performance gains.

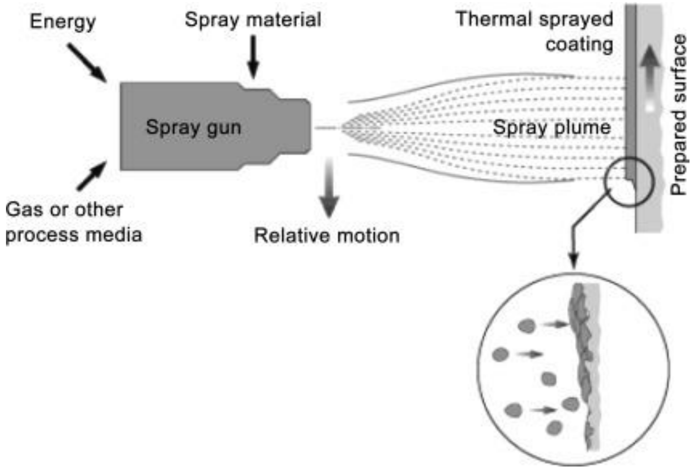

Figure 1. Thermal spray coating (Melentiev vd., 2022:14).

Magnetron sputtering (PVD) coating Method

The magnetron sputtering technique, based on physical vapor deposition (PVD), operates on the principle of ejecting atoms from a target material within a plasma environment and transporting them onto the substrate surface. As a result, thin and uniform films ranging from the nanometer to micrometer scale can be produced. This method offers precise control over surface roughness and chemical composition; however, the processing cost is relatively high (Figure 2).

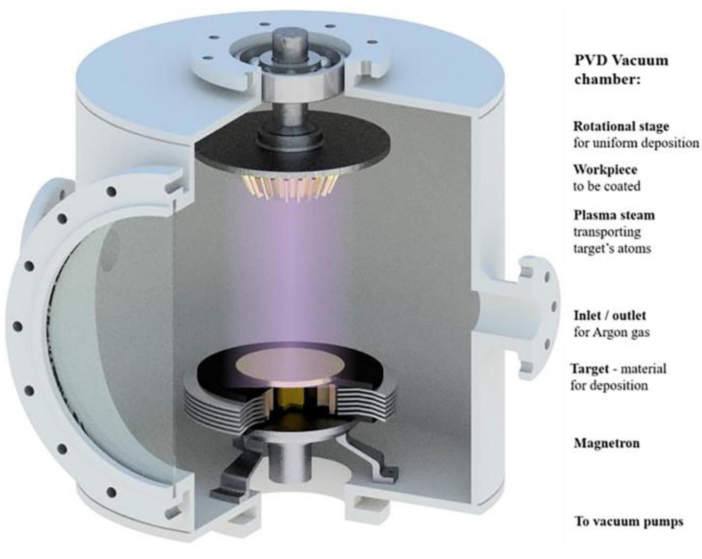

Figure 2. Scheme of the magnetron sputtering deposition process (Melentiev et al., 2022:3).

Spin and dip coating methods

Thin coatings can be produced by applying suspensions containing graphene, carbon nanotubes, metal oxides, or polymers onto a surface through spin coating or dip coating processes. These methods are cost-effective and particularly advantageous for forming nanoscale layers. However, their relatively low mechanical durability presents a drawback for long-term applications (Figure 3).

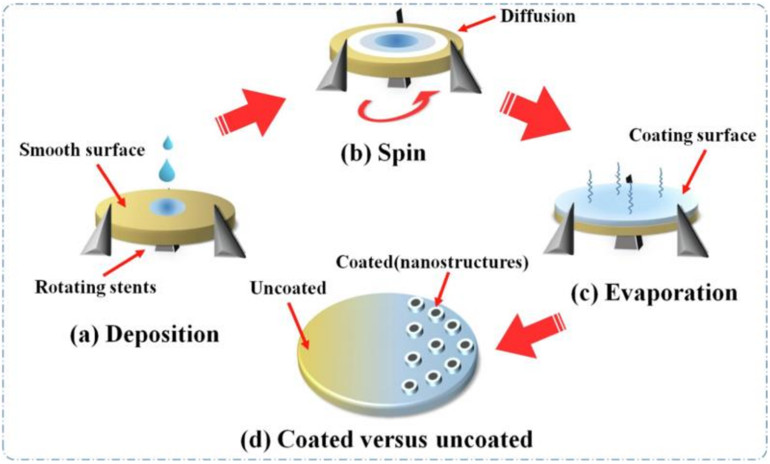

Figure 3. Spinning coating method (Chu et al., 2022:7).

Laser texturing thermal processing method

In this technique, the high energy density of a laser beam is used to create geometric features such as grooves, cavities, or micropillars on the surface. These microstructural patterns allow precise control over bubble nucleation and detachment processes. However, the method has disadvantages, including increased processing time and cost for large-area surfaces.

Mechanical surface roughening methods

Mechanical roughening processes such as sandblasting, grinding, or abrasive brushing represent the simplest physical modification techniques. By increasing surface roughness, they facilitate bubble nucleation; however, they do not provide fine control over micro- or nanoscale structural features.

Chemical Coating Methods

Chemical modification techniques create new compositions or structures on the surface through controlled chemical reactions, deposition processes, oxidation, or surface activation mechanisms. Their most significant advantage is the ability to directly tailor the surface's wettability (hydrophilic/hydrophobic behavior) and nanoscale structure.

Electrochemical deposition (electrodeposition) method

In this method, metallic or oxide nanoparticles are deposited onto the surface from an electrolytic bath, forming porous and irregular micro/nano structures (Figure 4). Coating thickness, growth rate, and morphology can be precisely controlled through electrochemical parameters. Owing to these characteristics, electrodeposition is a highly effective technique for enhancing capillary wicking and tuning surface wettability.

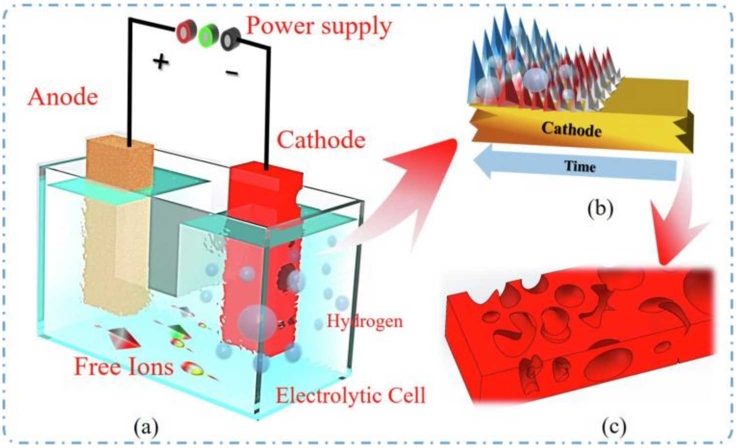

Figure 4. Electrochemical coating (Chu et al., 2022:9*)*.

Electrochemical anodization method

Anodic oxidation, commonly applied to metals such as aluminum, titanium, and magnesium, enables the formation of ordered nanoporous oxide layers. These structures exhibit high hydrophilicity, which enhances liquid replenishment and can lead to substantial increases in CHF.

Chemical vapor deposition (CVD) method

In the CVD process, reactive gases interact with the substrate at elevated temperatures to form a thin film (Figure 5). Carbon nanotubes, graphene, and various metal oxides can be produced using this technique. The resulting films typically possess strong adhesion and excellent thermal stability.

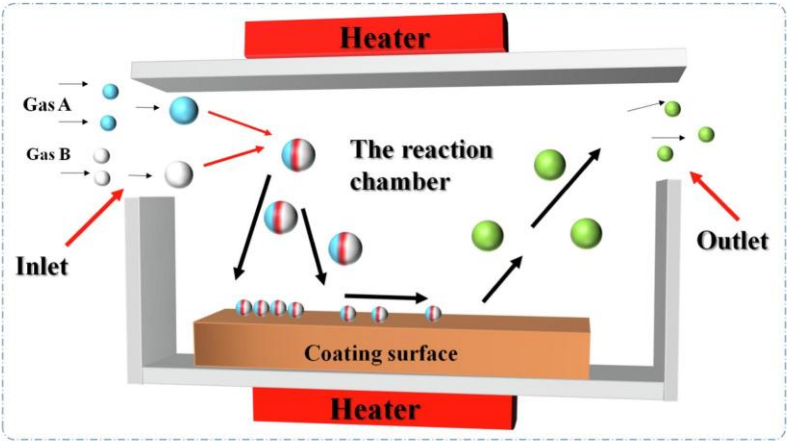

Figure 5. Chemical vapor deposition coating (Chu vd., 2022:8).

Sol–gel chemical deposition method

The sol–gel method is based on the hydrolysis and condensation of metal alkoxides to form a gel, enabling the fabrication of nanoporous ceramic coatings at relatively low temperatures. This technique allows easy control of pore structure and film thickness on the resulting surfaces.

Chemical etching method

Chemical etching, performed using acidic or basic solutions, produces controlled microcavities and irregular rough structures on the surface. This treatment increases the number of bubble nucleation sites while also influencing surface wettability.

Chemical surface functionalization method

Through silanization, fluorocarbon coatings, or the introduction of oxide functional groups, the surface can be chemically modified to achieve superhydrophobic or superhydrophilic characteristics. In this way, bubble departure dynamics, liquid film stability, and the wetting angle can be directly controlled.

Comparison of Physical and Chemical Surface Modifications

The choice of surface modification method depends on the requirements of the intended application. Physical techniques generally produce thicker coatings with higher roughness and robust mechanical structures, whereas chemical methods yield thinner films that are chemically functionalized and provide precise control over surface wettability. While physical coatings offer advantages such as enhanced HTC and increased bubble nucleation site density, chemical modifications often have a more pronounced impact on CHF improvement due to their ability to enhance capillary wicking and control wettability. In recent literature, multi-scale hybrid surfaces that combine both approaches stand out as the highest-performing solutions.

HEAT TRANSFER ENHANCEMENT MECHANISMS

In pool boiling processes, surface modification not only alters the geometric or chemical characteristics of a surface but also influences the fundamental stages of boiling—bubble nucleation, growth, departure, and surface rewetting. By affecting these microscale dynamics, surface treatments can yield significant improvements in both HTC and CHF. Studies in the literature demonstrate that performance enhancements achieved through coatings and structural modifications generally arise from the simultaneous action of multiple mechanisms rather than a single dominant factor. The key mechanisms are examined in detail below.

Bubble Dynamics and Nucleation Site Density

Surface modifications can increase both the number and distribution of active sites available for bubble formation. Rough, porous, or micro/nanostructured coatings provide significantly more nucleation sites compared to flat, polished surfaces, enabling a much denser initiation of bubbles. An increase in nucleation site density reduces the required wall superheat at the onset of boiling, allowing bubble formation to begin earlier and enhancing boiling heat transfer from the initial stages.

Additionally, bubble growth and departure behavior are strongly influenced by surface topography. Micro- or porous surfaces modify bubble anchoring, growth rates, and departure frequency. As a result, the increase in both the number and effectiveness of nucleation sites plays a major role in improving the heat transfer coefficient.

Surface Wettability

The hydrophilic or hydrophobic nature of a surface significantly influences key boiling phenomena such as bubble nucleation, liquid replenishment, and the transition to film boiling. Hydrophilic surfaces promote strong liquid spreading and wetting, ensuring rapid rewetting after vapor bubbles detach from the surface. This delays the formation of dry spots, postpones the onset of film boiling, and ultimately increases CHF.

Conversely, hydrophobic surfaces facilitate bubble nucleation, leading to higher bubble formation rates and greater bubble population density. However, because hydrophobicity weakens liquid replenishment, it can reduce CHF despite enhancing nucleation.

For this reason, many modern approaches focus on mixed-wettability, biphilic, or superbiphilic surfaces, where regions of differing wettability coexist on the same substrate. In some designs, hydrophobic zones promote bubble nucleation while adjacent hydrophilic regions support liquid spreading and rewetting. Numerous studies have shown that such engineered surfaces provide a balanced enhancement of both HTC and CHF.

Porosity, Capillary Effect (Wickability), and Liquid Replenishment

Micro/nanostructures or porous coatings created through surface modification enable capillary-driven liquid replenishment behind vapor bubbles during boiling. This mechanism becomes especially critical at high heat flux conditions. Porous structures can rapidly draw liquid into the regions vacated by departing bubbles, thereby preventing or delaying the formation of dry spots. As a result, the transition to film boiling and eventual burnout is postponed, leading to an increase in CHF.

Multi-scale porous architectures—such as the combination of fine nanoporous networks with larger microcavities—provide additional advantages by balancing liquid replenishment, bubble nucleation, and vapor escape pathways. For this reason, wickability, or the surface's ability to draw and transport liquid via capillary forces, is a key performance determinant in coated and structured boiling surfaces.

Surface Roughness and Effective Heat Transfer Area

Another fundamental effect of surface modification is the alteration of surface geometry. Structural features such as roughness, microcavities, protrusions, grooves, and channels can increase both the effective heat transfer area and the number of favorable nucleation sites. Enhanced roughness leads to more bubble interaction zones and consequently higher bubble generation rates.

Engineered microchannel or porous geometries can further regulate flow by separating liquid and vapor pathways, minimizing bubble coalescence, and preventing vapor accumulation. These improvements contribute to simultaneous enhancements in both HTC and CHF. Moreover, microstructured surfaces with enlarged effective area support more efficient evaporation and convection by expanding the active heat transfer interface.

Hybrid Mechanisms (Multiscale Structures and Combined-Feature Surfaces)

Research has shown that no single mechanism is typically sufficient to achieve substantial enhancement in boiling heat transfer. Multiscale (multi-level) structures and hybrid surface features provide significant advantages for boiling performance. In particular, surfaces that are micro-structured and subsequently coated with nanoscale layers promote multiple beneficial effects simultaneously enhanced bubble nucleation, increased surface area, improved capillary liquid transport, and superior surface wettability.

Such hybrid architectures improve all major stages of the boiling process, including nucleation, liquid supply, vapor removal, and surface rewetting. As a result of these combined and synergistic mechanisms, notable simultaneous increases in both HTC and CHF can be achieved.

INTERACTION OF MECHANISMS AND DESIGN PRINCIPLES

Maximizing heat transfer performance through surface modification cannot be achieved by focusing on a single parameter. Instead, the following key factors must be considered together:

- Bubble nucleation site density and distribution (micro/nano structures)
- Surface wettability and appropriate contact angle/surface energy
- Porosity and capillary-driven liquid replenishment (wickability)
- Surface geometry/roughness/channels and the separation of liquid–vapor pathways
- Combined effects enabled by multiscale (micro + nano) structuring

An optimal balance among these parameters is essential. For example, a highly porous but hydrophobic surface may produce abundant bubbles, yet inadequate liquid replenishment can prevent any improvement in CHF. Similarly, channels designed solely to enhance liquid supply may inadvertently restrict vapor escape, causing vapor accumulation and premature transition to film boiling.

Therefore, effective surface design requires simultaneous optimization of bubble dynamics and liquid/vapor flow management. Table 1 summarizes the advantages and disadvantages of commonly used surface coating methods.

Table 1. Advantages and disadvantages of surface coating methods.

Coating/Surface Modification Method	Advantages	Disadvantages/Limitations
Physical Spraying Supersonic Spraying Plasma Thermal Spraying	-Creates a porous/rough, high–surface-area layer that increases the number of nucleation sites. -Enhances capillary wicking and supports rapid rewetting of the surface. -Offers strong potential for improving both HTC and CHF. -The porous structure helps balance bubble generation and the liquid–vapor transport cycle.	-The coating can be relatively thick, which may introduce additional thermal resistance. -Excessive porosity can lead to undesirable effects such as vapor blockage, insufficient liquid supply, or pore clogging. -The long-term durability of the coating—particularly its mechanical and thermal cycling resistance—may be uncertain, raising concerns about long-term stability.
Physical Thin Film (PVD/Sputtering/Magnetron Sputtering, etc.)	-Enables the formation of very thin and uniform films, ensuring good thermal contact with the substrate. -Nanostructured surfaces can provide microscopic nucleation sites and increased effective surface area. -Because the coating thickness is low, the added thermal resistance is generally minimal.	-Due to the thin-film nature of the coating, porosity, capillary structures, and wicking capabilities may be limited; consequently, liquid replenishment capacity is generally lower than that of porous spray coatings. -If the application requires not only increased roughness/surface area but also microstructures that guide liquid–vapor pathways or provide strong capillary feeding, this method may be insufficient.

		-Large-area deposition can be challenging, and the equipment requirements (vacuum systems, sputtering units, etc.) may lead to high implementation costs.

Table 1. Continuing.

Physical – Mechanical/ Structure formation (e.g., groove/channel/ microstructure/texture)	-Enables controlled modification of surface geometry and the creation of tailored micro-channel structures, providing advantages for bubble nucleation, vapor escape, and separation of liquid–vapor flow paths. -Allows optimization of the balance between wicking, capillary liquid supply, and vapor removal, enabling significant improvements in both CHF and HTC. -Supports synergy through combined nano- and micro-scale structuring (multiscale architecture), yielding simultaneous enhancements in bubble nucleation, wettability, and liquid replenishment.	-Fabricating such structures and performing the required surface modifications can be complex, often necessitating precise processing steps and specialized equipment (e.g., laser texturing, micro-machining, advanced surface treatment tools). -Large-scale manufacturing and industrial implementation can be challenging; cost and scalability may be limiting factors. -Determining the optimal geometry of micro-/channel structures is critical; excessively deep or narrow channels, or improper pitch/feature sizing, can hinder liquid replenishment or obstruct vapor removal, negatively affecting performance.

Table 1. Continuing.

Chemical – Electrochemical (Electrodeposition, Anodization, etc.)	-Enables the formation of porous micro/nano-structured layers, which enhances the number of nucleation sites and supports capillary wicking and efficient rewetting. -Coating thickness, porosity, and morphology can be precisely tuned through electrochemical parameters, allowing optimization of the resulting surface characteristics. -The porous, multiscale micro/nanostructures achievable with this method can significantly improve both HTC and CHF. -These coatings are typically more "chemically bonded" to the substrate, offering advantages in long-term stability and mechanical/thermal durability.	-The electrochemical deposition process is highly sensitive to operating parameters (current density, deposition time, ion concentration in the bath, etc.), requiring strict control; reproducibility may be challenging. -Excessively thick or overly porous layers can lead to gas/vapor clogging or pore blockage, disrupting the desired balance between wicking, wetting, and vapor removal. -In some chemical deposition methods, substrate–coating compatibility and mechanical adhesion can be problematic; risks of delamination or cracking—especially under thermal cycling—must be carefully evaluated.

PERFORMANCE ENHANCEMENTS REPORTED IN THE LITERATURE

Significant improvements in heat transfer performance have been reported in the literature for surfaces modified using various techniques. In a study by Ranjan et al. (2023), plasma-sprayed surfaces exhibited an increase of approximately 55–68% in HTC and nearly a 2.4-fold enhancement in CHF. In another study employing micro-nano porous coatings and nanostructured layers, researchers observed notable increases in both HTC and CHF during boiling with water as well as dielectric fluids (Pereira et al., 2024). Ye et al. (2024) investigated surfaces with mixed-wettability patterns and demonstrated that the balance between bubble nucleation and rewetting enabled exceptionally high performance, resulting in dramatic improvements in HTC and CHF compared to conventional surfaces.

These findings indicate that surface modification can provide not just incremental gains but potentially step-change enhancements in pool boiling heat transfer performance.

LIMITATIONS AND KEY CONSIDERATIONS

Different studies employ various working fluids, surface materials, coating techniques, and experimental conditions. Therefore, application-specific requirements -such as the working fluid, heat flux range, and substrate material- must be carefully considered during surface design. Porous and multilayered surfaces may experience long-term issues such as degradation, fouling, wear, or clogging, which can lead to performance decline in practical applications. A high-performance surface design cannot rely on a single parameter; instead, it depends on the balanced integration of all mechanisms discussed above. Poorly optimized designs may enhance certain mechanisms while inadvertently suppressing others.

CONCLUSION AND ASSESSMENT

Surface modification is among the most effective passive strategies for improving heat transfer in pool-boiling applications. As outlined in this section, such enhancement typically results from the combined action of multiple mechanisms, including increased nucleation site density (bubble dynamics), improved surface wettability, capillary liquid replenishment, modified surface roughness and geometry, and multiscale micro–nano structuring. Therefore, an optimal modified surface design must consider not only porous coatings or hydrophilic/nanostructured layers, but also the chemical nature of the surface (wettability), micro–nano architecture, capillary flow pathways, surface topography, and the optimization of liquid and vapor transport routes.

In conclusion, surface modification not only increases the heat transfer coefficient but also elevates the critical heat flux limit, enabling pool-boiling systems to operate safely and efficiently under significantly higher thermal loads.

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Key Parameters Affecting Pool Boiling Heat Transfer

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ABSTRACT

In this section, the multicomponent interaction mechanisms governing pool boiling heat transfer are examined through an integrated and holistic perspective. The onset of boiling, bubble nucleation, growth, and the progression toward the critical heat flux (CHF) are strongly dictated by the physical and chemical characteristics of the heated surface, as well as the thermophysical properties of the working fluid. Within this context, the roles of surface wettability, roughness and topography, porous–capillary structures, material thermal conductivity, and the influence of surface modifications on bubble dynamics are analyzed. Additionally, key fluid properties—including surface tension, viscosity, density difference, thermal conductivity, specific heat capacity, and latent heat of vaporization—are discussed in relation to their critical impact on the heat transfer coefficient, bubble generation frequency, and the transitions between boiling regimes.

The subsequent part of the section explains how operating conditions and geometric factors dictate boiling performance. The effects of temperature difference, system pressure, heat flux, and liquid height on bubble behavior and CHF are evaluated. Moreover, the influence of surface shape, size, and orientation on bubble detachment and flow organization is addressed. Finally, the way microscopic processes such as bubble nucleation, growth, departure, and vapor layer formation govern macroscopic heat transfer performance is elucidated.

This comprehensive framework highlights the multifaceted nature of pool boiling heat transfer and establishes a solid scientific foundation for designing high-efficiency thermal systems.

Keywords – Pool boiling heat transfer, surface properties, bubble dynamics, thermophysical fluid properties, critical heat flux

INTRODUCTION

Boiling is one of the most effective phase-change heat transfer mechanisms, capable of achieving extremely high heat fluxes. For this reason, it plays a critical role in energy systems, electronics cooling, nuclear reactors, chemical processing, and many other industrial applications. Among various boiling modes, pool boiling has a special significance because the fluid motion is not externally forced; instead, natural bubble dynamics govern the entire process. In pool boiling, the heat transfer coefficient results from the simultaneous action of multiscale phenomena such as bubble nucleation and growth, vapor–liquid interfacial interactions, and microlayer evaporation. Each of these processes is shaped by the complex interplay among surface characteristics, fluid thermophysical properties, operating conditions, and system geometry.

In this chapter, the fundamental parameters affecting pool boiling heat transfer are examined under five main categories. The first section discusses the influence of surface properties -such as roughness, wettability, porosity, and coating types- on bubble nucleation and heat transfer performance. The second section explores how fluid thermophysical characteristics, including surface tension, viscosity, density difference, and latent heat, govern boiling regimes and bubble dynamics. The third section focuses on operating conditions such as temperature difference, pressure, and heat flux, explaining how these variables direct boiling behavior. The fourth section evaluates the effects of geometric factors -heater shape, orientation, and size- on bubble departure and flow organization. Finally, bubble dynamics are investigated at the microscopic scale, including nucleation frequency, departure diameter, bubble interactions, and vapor-layer formation.

This comprehensive perspective demonstrates that pool boiling is not governed by a single variable; rather, it emerges from a multidimensional and highly coupled set of mechanisms. The analyses provided throughout the chapter aim both to deepen the scientific understanding of pool-boiling heat transfer and to establish a theoretical foundation for engineering strategies used in the design of high-performance thermal systems.

SURFACE PROPERTIES

Pool boiling heat transfer is strongly governed by the physical, chemical, and morphological characteristics of the heated surface. The structure of the surface directly influences bubble nucleation, bubble growth cycles, vapor–liquid interfacial stability, and CHF. Therefore, precise engineering of surface properties is one of the most fundamental strategies for enhancing boiling performance. In this section, surface characteristics are examined in terms of wettability, roughness, porosity, material properties, and the types of coatings or surface modifications applied.

Surface Wettability (Contact Angle)

Wettability describes the tendency of a liquid to spread over a surface and is commonly characterized by the contact angle. A low contact angle (hydrophilic surface) promotes stronger liquid–surface interaction, ensuring continuous rewetting of the heater surface. This enhances the CHF and improves the overall stability of the boiling process. Conversely, a high contact angle (hydrophobic surface) facilitates bubble nucleation and increases bubble departure frequency. However, on highly hydrophobic surfaces, the vapor film may form prematurely, potentially destabilizing the heat transfer process (Figure 1). Surface wettability can be precisely controlled through surface-energy modification, chemical treatments, or specialized coatings, enabling the design of surfaces with tailored boiling characteristics (Xiang et al., 2024:10).

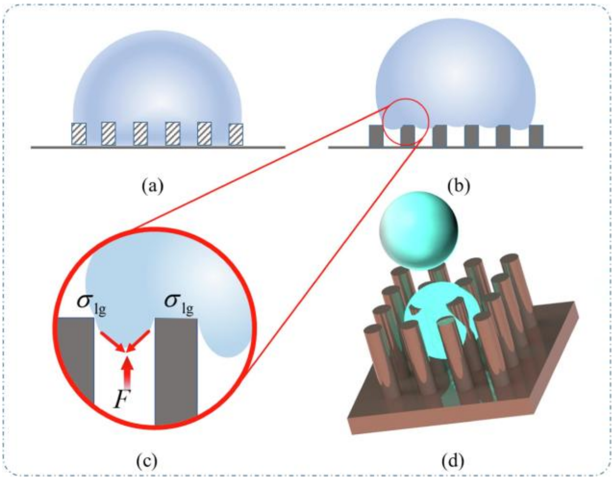

Figure 1. Schematic representation of droplet contact angle on hydrophilic and hydrophobic surfaces (Chu et al. 2022:13).

Surface Roughness and Topographical Structure

Surface roughness and topography are among the most critical parameters governing both the number and size of active nucleation sites (Figure 2). Micro- and nanoscale asperities create cavities where vapor bubbles can be trapped, thereby increasing the number of nucleation sites and promoting more uniform bubble departure behavior (Dadjoo et al., 2017:354). This enhancement in nucleation activity leads to improved boiling heat transfer. However, excessive roughness may induce premature bubble coalescence, which can disrupt liquid replenishment and undermine the heat-transfer mechanism. Therefore, careful optimization of surface topography is essential to achieve a balance between enhanced nucleation and stable boiling performance.

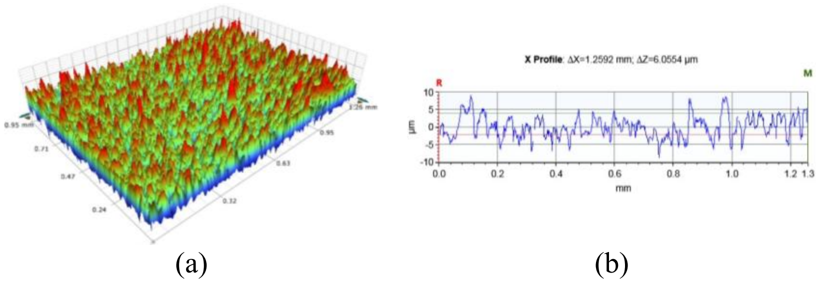

Figure 2. (a) 3D area image and (b) Ra plot of a Ni-coated heating surface with a Cu substrate.

Porous Surfaces and Capillary (Wicking) Structures

Porous surfaces and capillary structures significantly enhance boiling performance by actively transporting liquid across the heated surface (Figure 3). Through capillary pumping, porous or wick-like structures continuously supply fresh liquid to the surface, delaying the formation of hot spots and thereby increasing CHF.

The effectiveness of these structures depends on several factors, including pore size, pore distribution, interconnectedness, and the resulting capillary pressure. Common surface types used to achieve such effects include metal foams, sintered coatings, and micro/nanoporous layers (Xiang et al., 2024:17).

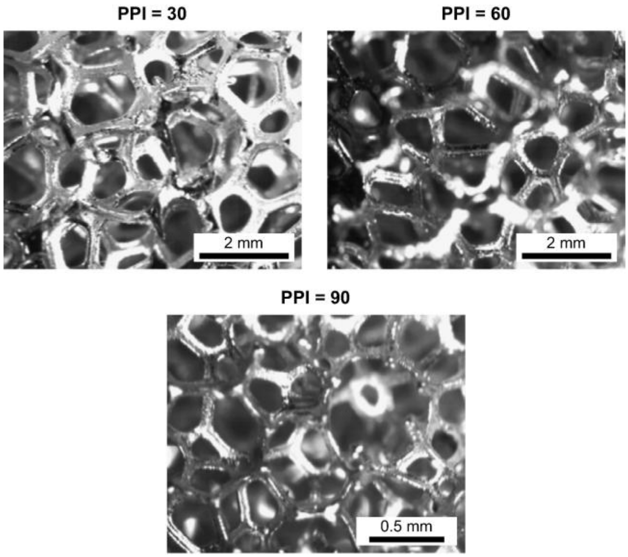

Figure 3. Images of copper foam with three different porosities (Yang et al., 2010:1229).

Surface Material and Thermal Conductivity

The material of the heating surface is one of the fundamental determinants of thermal performance in boiling processes. Materials with high thermal conductivity (e.g., copper, silver) promote a more uniform surface temperature distribution, enabling vapor bubbles to grow and detach in a more stable manner across the surface. In contrast, low-conductivity materials tend to develop localized hot spots, which can degrade boiling performance. Additionally, the chemical stability and corrosion resistance of the surface material are critical for long-term boiling applications operating at elevated temperatures (Xiang et al., 2024:23; Foster et al., 2026:8).

Coating and Surface Modification Type

Coatings and surface modification techniques are widely employed engineering solutions aimed at improving boiling performance. These methods can be used to tune surface energy, generate micro- or nanostructures, introduce porous layers, and impart hydrophilic or hydrophobic characteristics (Figure 4).

Common coating approaches include high-velocity oxy-fuel spraying (HVOF), physical vapor deposition (PVD), chemical vapor deposition (CVD), anodization, sintering, and nanoparticle-based coatings. Such techniques enhance the number of nucleation sites, thereby significantly increasing both the heat transfer coefficient (HTC) and the CHF.

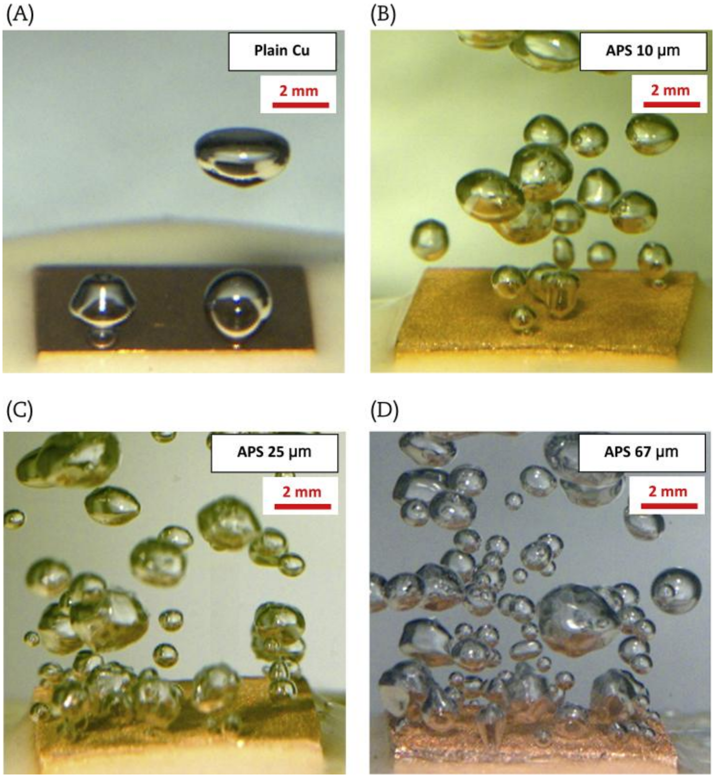

Figure 4. Images of nucleate boiling on pure and microporous surfaces (Jun vd., 2016:937).

THERMOPHYSICAL PROPERTIES OF THE BOILING FLUID

Pool boiling heat transfer depends not only on the characteristics of the heated surface but also strongly on the thermophysical properties of the boiling fluid. These properties directly influence bubble nucleation, growth, detachment, and surface rewetting mechanisms, thereby determining both the heat transfer coefficient and the critical heat flux. In this section, the impacts of surface tension, viscosity, density, thermal properties, and latent heat of vaporization on overall boiling performance are examined.

Surface Tension

Surface tension represents the cohesive force acting at the liquid–vapor interface and plays a critical role in bubble nucleation. Low surface tension facilitates bubble formation, increasing the number of active nucleation sites and accelerating boiling heat transfer. In contrast, high surface tension requires greater energy for bubble initiation, raising the nucleation threshold and reducing bubble departure frequency. For this reason, surface tension often becomes a limiting factor in fluids with inherently high surface tension, such as water.

Viscosity

Viscosity is a measure of the fluid's resistance to flow and directly influences bubble growth and departure from the heated surface. Low-viscosity fluids allow bubbles to rise more rapidly and detach more easily, resulting in higher heat transfer coefficients. In high-viscosity fluids, bubble rise velocity decreases, attachment time increases, and bubble coalescence becomes more likely, leading to a reduction in heat transfer performance. Because viscosity also governs liquid replenishment near the wall, it plays a significant role in determining the critical heat flux.

Density

The density difference between the liquid and vapor phases is a key factor shaping bubble dynamics. A large density difference promotes faster bubble buoyancy and delays the formation of vapor blankets on the surface. Conversely, a small density contrast causes bubbles to remain attached to the surface longer, restricting heat transfer. Vapor density also influences the internal pressure of bubbles, affecting bubble shape and departure frequency.

Thermal Conductivity and Specific Heat

The thermal conductivity and specific heat of the working fluid determine how effectively heat is transported from the heated surface into the liquid. Fluids with high thermal conductivity remove heat rapidly, creating favorable temperature gradients that support sustained bubble nucleation and high heat transfer coefficients. Fluids with high specific heat require more energy for a given temperature rise, helping stabilize the thermal boundary layer near the surface. Together, these properties significantly influence performance in the nucleate boiling regime.

Latent Heat of Vaporization

The latent heat of vaporization is the amount of energy required to transform a unit mass of liquid into vapor, and it directly affects the efficiency of the boiling process. Fluids with high latent heat can produce more vapor at the same heat flux, enhancing bubble generation and improving HTCs. However, a very high latent heat implies that more energy must accumulate at the surface before nucleation occurs, which can alter bubble waiting times. Therefore, achieving optimal boiling performance requires careful consideration of latent heat in relation to operating temperature and pressure.

OPERATING CONDITIONS

Pool boiling heat transfer depends not only on the properties of the surface and the working fluid but also strongly on the operating conditions of the system. These conditions directly influence the onset of boiling, bubble nucleation behavior, surface rewetting, and the dynamics leading up to the critical heat flux. Therefore, proper control of system temperature, pressure, applied heat flux, and liquid level is essential for achieving stable and high-performance boiling (Sattari et al., 2014:106).

Superheat ($\Delta T = T_w - T_{sat}$)

The temperature difference between the heated surface and the saturation temperature of the fluid is the primary driving force of boiling heat transfer. At low superheat levels, bubble nucleation is limited and boiling remains in its incipient stage. As ΔT increases, bubble departure frequency rises, liquid–vapor interactions intensify, and the heat transfer coefficient improves. However, excessive superheat can lead to the formation of a vapor blanket on the surface, triggering the Leidenfrost effect and causing a sudden drop in heat transfer. Thus, superheat is one of the most sensitive parameters governing the stability of the boiling regime.

Operating Pressure

Pressure is a key environmental variable that influences the saturation temperature of the fluid and the dynamics of bubble formation. As pressure increases, the saturation temperature rises and bubble nucleation requires more energy. Under these conditions, bubbles tend to be smaller and may detach more frequently. At low pressure, bubbles form at larger volumes and remain attached to the surface for longer periods, increasing bubble coalescence and potentially degrading heat transfer. Proper selection of operating pressure is crucial for controlling the critical heat flux and maintaining stable boiling behavior.

Heat Flux (q")

Heat flux is the rate of heat transferred from the surface to the fluid per unit area and plays a central role in defining the boiling regime. At low heat fluxes, convection and the early stages of nucleate boiling dominate. As heat flux increases into the medium and high range, bubble generation intensifies, bubble interactions become more frequent, and nucleate boiling becomes the dominant heat transfer mechanism. At extremely high heat fluxes, decreased liquid contact with the surface leads to vapor film formation, pushing the system toward the CHF point, after which heat transfer deteriorates. Controlled adjustment of heat flux is therefore essential for optimizing boiling performance.

Liquid Level and Pool Depth

The height of the liquid column affects bubble rise behavior and the rewetting of the heated surface. Adequate pool depth minimizes the impact of bubble agitation near the surface and promotes stable liquid replenishment. At shallow liquid levels, bubbles reach the free surface rapidly, reducing liquid recirculation and potentially causing vapor accumulation. Pool depth also influences hydrostatic pressure, which indirectly affects saturation temperature and bubble dynamics. For this reason, the optimal liquid level should be selected based on system geometry and operating conditions.

GEOMETRIC FACTORS

Pool boiling heat transfer is strongly influenced by the geometric characteristics of the heated surface. The shape, size, orientation, and three-dimensional configuration of the surface directly govern bubble density, bubble departure mechanisms, and liquid replenishment behavior. As a result, geometric factors play a critical role in determining overall boiling performance and must be carefully engineered to optimize heat transfer.

Shape, Orientation, and Size of the Heating Surface

The shape (planar, cylindrical, spherical, etc.), orientation (vertical, horizontal, inclined), and size of the heating surface exert a strong influence on bubble formation and bubble departure behavior. Surface geometry governs how bubbles grow, detach, and move, while also affecting the replenishment of liquid returning to the surface. Cylindrical and spherical heaters often allow bubbles to slide along the curvature before detaching, whereas flat surfaces typically exhibit vertically oriented bubble departure patterns. As the geometry changes, both bubble departure frequency and bubble size are altered correspondingly (Figures 5 and 6).

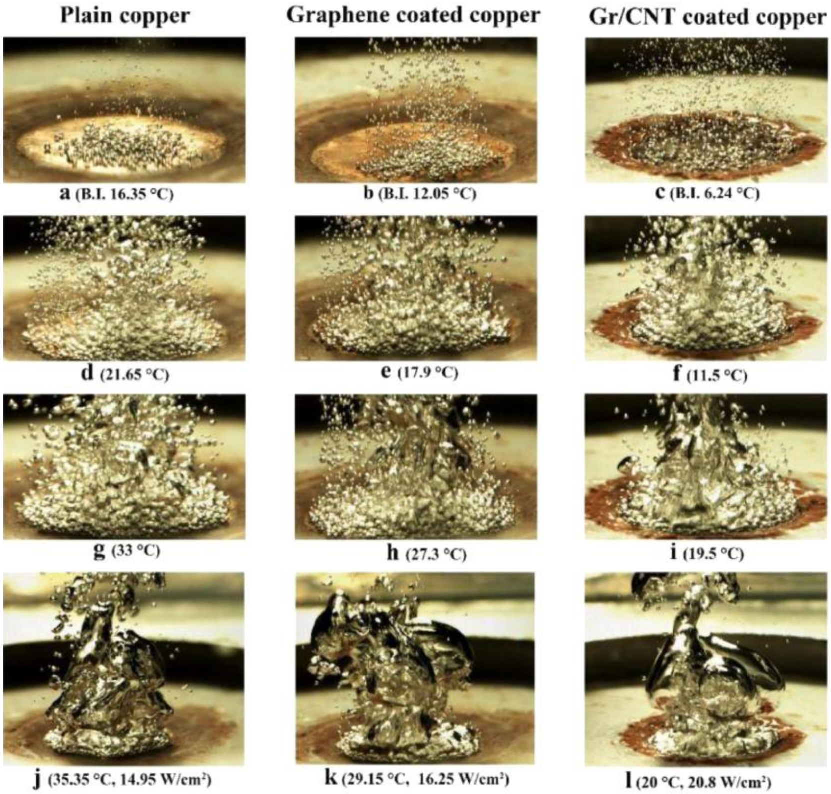

Figure 5. Bubble formation on a flat surface under different surface conditions and heat fluxes (Kumar et al., 2018:502).

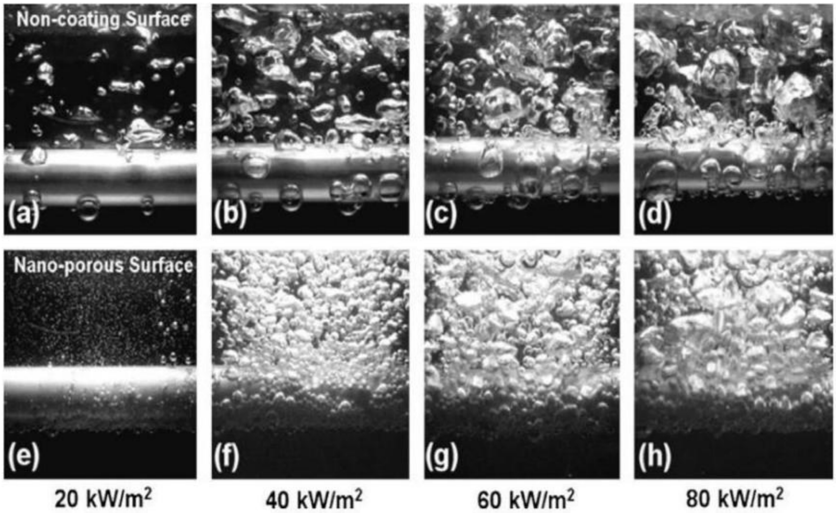

Figure 6. Bubble formation on a horizontal cylindrical surface under different surface conditions and heat fluxes (Lee et al., 2010:4277).

On the other hand, the orientation of the heating surface plays a critical role. Horizontal surfaces typically promote a more stable nucleate boiling regime, as bubbles detach vertically in a uniform manner. On vertical surfaces, bubbles slide upward along the wall, which can enhance liquid replenishment to the heated area and, in some cases, lead to higher heat transfer. Inclined surfaces exhibit a hybrid behavior that combines both mechanisms, creating unique boiling dynamics. Surface orientation strongly influences bubble coalescence, interaction, and the degree of bubble superposition.

The size of the heating surface also affects boiling performance. Larger surfaces can accommodate a greater number of nucleation sites, enabling higher heat fluxes. Conversely, on smaller surfaces, edge effects become dominant, and bubble behavior is more strongly influenced by boundary conditions. For this reason, the surface dimensions must be optimized according to the specific application and operating requirements.

Edge Effects and Three-Dimensional Surface Structure

The edges and three-dimensional (3D) structural features of a heating surface are significant geometric factors influencing boiling behavior. Edge regions often serve as preferential nucleation sites where bubbles can more easily form, increasing the local nucleation site density. Additionally, temperature gradients near edges can accelerate bubble generation. On smaller surfaces, edge effects are more pronounced and can dominate overall boiling performance.

The 3D structure of a heating surface -including protrusions, channels, cavities, or multilayered features- substantially alters bubble dynamics and liquid flow. Micro- or macro-scale 3D structures enable controlled nucleation and directional guidance of bubbles. Channel features facilitate active liquid transport, enhancing CHF. Cavities that trap bubbles act as continuous active nucleation centers, increasing HTC. Overall, 3D surface designs are considered among the most effective modern strategies for enhancing pool boiling heat transfer.

BUBBLE DYNAMICS

Bubble dynamics constitute the fundamental mechanism of pool boiling heat transfer. The formation, growth, detachment, and interaction of bubbles on the surface directly determine how effectively the surface is re-wetted by liquid, the duration of vapor generation, and the overall HTC (Figure 7). Therefore, a thorough understanding of bubble behavior is crucial for both developing accurate theoretical boiling models and designing optimized surface modifications.

Bubble Formation Frequency

Bubble formation frequency (f) refers to the number of bubbles generated per unit time at a single nucleation site. Higher bubble frequencies accelerate liquid replenishment on the surface, enhancing HTC. Conversely, at low frequencies, bubbles remain on the surface longer, potentially limiting liquid contact. Bubble frequency is influenced by surface temperature, wettability, surface roughness, and the thermophysical properties of the fluid. An increase in frequency corresponds to more effective heat transfer in the nucleate boiling regime.

Bubble Departure Diameter

The diameter of a bubble at detachment from the surface is a critical characteristic of the boiling process. A larger departure diameter indicates bubbles grow longer on the surface, increasing the risk of vapor coverage and local dry spots. Smaller departure diameters indicate rapid detachment, facilitating efficient re-wetting of the surface. Departure diameter is determined by multiple factors, including surface tension, density difference, viscosity, surface geometry, and orientation. Surface energy modifications, such as hydrophilic treatments, are commonly employed to control bubble departure diameter.

Bubble Interaction

Bubbles rarely exist in isolation during boiling. Multiple bubbles form simultaneously and interact with neighboring bubbles, leading to growth, coalescence, and detachment. Coalescence can produce larger bubble clusters, increasing the tendency for vapor to blanket the surface. Bubble repulsion or guidance can alter local flow patterns, either enhancing or reducing HTC. These interactions are directly related to bubble density and applied heat flux. At high heat fluxes, bubble superposition becomes more pronounced, approaching the transition to film boiling.

Vapor Layer Formation

A vapor layer forms when a continuous film of vapor develops between the heating surface and the liquid, which is characteristic of the film boiling regime observed after CHF This layer dramatically reduces HTC by inhibiting direct liquid contact. Unstable vapor layers may exhibit oscillation or rupture, while fully stable layers lead to the Leidenfrost effect. Delaying the formation of this vapor layer is a primary objective in designing high-performance boiling surfaces. Surface thermal conductivity, wettability, and porosity directly influence the tendency for vapor layer formation.

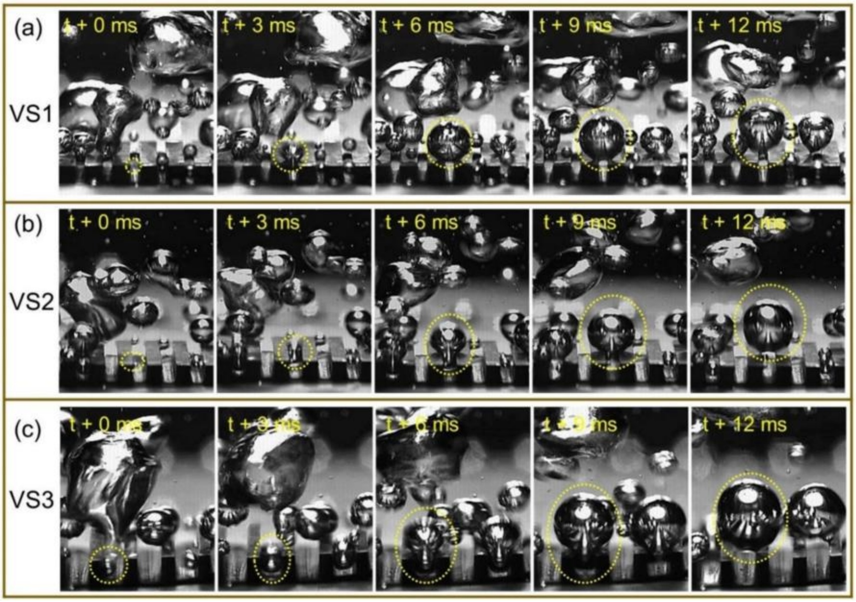

Figure 7. Vapor bubble formation, growth, and detachment from different surfaces (Li et al., 2025:8).

CONCLUSION

This section has provided an engineering-focused evaluation of the key parameters governing pool boiling heat transfer. The analysis demonstrates that the micromorphological characteristics of the heating surface -such as wettability, roughness, porosity, and coating type- play a critical role in nucleation site formation and in enhancing HTC. Meanwhile, the thermophysical properties of the working fluid, including surface tension, viscosity, density difference, and latent heat of vaporization, define the boundaries of boiling regimes, directly influencing CHF and maximum performance points.

Operating conditions, along with surface geometry and orientation, regulate microdynamic processes such as bubble formation frequency, departure diameter, and vapor layer development, which collectively determine macroscopic heat transfer efficiency. These findings indicate that pool boiling performance cannot be optimized by a single parameter; instead, surface design, fluid selection, operating conditions, and geometric features must be considered in an integrated manner.

In conclusion, improving boiling heat transfer requires a multiscale design approach, combining surface engineering with thermophysical analysis to achieve optimal and reliable thermal performance.

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Vector-Loop Based Kinematic Analysis and Lagrangian Dynamics of a Five-Bar Parallel Robot

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ABSTRACT

This study presents the kinematic and dynamic modeling of a planar five-bar robotic mechanism. The kinematic analysis is established using vector loop equations in polar complex form, utilizing the Newton-Raphson method to solve for the unknown angular positions of the passive joints. Expressions for the position, velocity, and acceleration of the center of mass for each link are derived. Subsequently, the dynamic equations of motion are formulated using Lagrange's method. By evaluating the total kinetic energy of the system and assuming negligible gravitational potential energy, the required input torques for the actuated joints are calculated to facilitate precise control of the end-effector.

Keywords –Five-bar, Dynamic model, Robotic mechanism, Parallel manipulators, Euler-Lagrange approach

INTRODUCTION

Parallel manipulators, such as the five-bar linkage mechanism, are widely utilized in robotic applications requiring high stiffness, speed, and precision. This paper focuses on the mathematical modeling of a five-bar mechanism where the motion is driven by two actuators located at the base joints (Link 1 and Link 4). The system is defined by a set of link lengths $L_n^i \epsilon \Re^5$, link masses, and inertias, aiming to control the trajectory of the end-effector point $\boldsymbol{p}$. The modeling process begins with a kinematic analysis to determine the positions and velocities of the center of mass for all links. Due to the closed-chain constraints, the relationship between the active input angles Θ_1 , Θ_4 and the passive angles Θ_2 , Θ_3 is non-linear, requiring numerical solutions via the Newton-Raphson method. Following the kinematic resolution, the dynamic behavior of the system is analyzed. The equations of motion are derived using the Euler-Lagrange approach, which relies on the total kinetic energy of the system's components to compute the generalized torques τ_1 and τ_4 required for the actuators.

The Jacobian calculation for the five-bar robot, which differs from standard robotic arms due to its closed-chain structure, Formulation can be found in (Chavdarov, 2005,10). (Campion et al.) present the Pantograph as a two-degree-of-freedom parallel haptic device optimized for high dynamic performance and good kinematic conditioning, capable of delivering accurate tactile feedback up to 400 Hz with approximately 10 µm displacement resolution. Alternatively, several legged robot studies adopt five-link mechanism–based leg architectures to place the motors on the main body, thereby reducing leg inertia (Bai et al., 2020), (Che et al., 2022:11), (Tirumala et al., 2019).

KINEMATIC AND DYNAMIC MODELING

The point where the end-effector is located is denoted by p, and in order to track the reference position instantaneously, links 1 and 4 of the robotic mechanism are actuated by the actuators τ_1 and τ_4. In the robotic five-bar mechanism, for n = {1, 2, …, 4}, the link lengths are represented by $L_n \in \Re^4$, while the link masses $m_n \in \Re^4$ and inertias $I_n \in \Re^4$ are specified accordingly. The kinematic and dynamic representations are given in Figure 1. L_5 denotes the distance between the two actuators. The angles θ_2 and θ_3 are dependent variables, expressed as:

$$\theta_2 = \theta_1 + \theta_2^+, \quad \theta_3 = \theta_4 + \theta_3^+$$

and their time derivatives:

$$\dot{\theta}_2 = \dot{\theta}_1 + \dot{\theta}_2^+, \quad \dot{\theta}_3 = \dot{\theta}_4 + \dot{\theta}_3^+$$

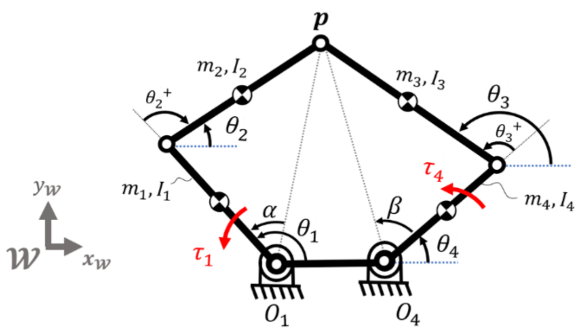

Figure 1. Up-view of Platform and kinematic and dynamic representations.

Positions and velocites of the center of mass of link 1;

$$x_1 = \frac{L_1 \cos(\Theta_1)}{2} + x_w$$

$$y_1 = \frac{L_1 \sin(\Theta_1)}{2} + y_w$$

$$\dot{x}_1 = -\frac{L_1 \sin(\Theta_1)\ \dot{\Theta}_1}{2}$$

$$\dot{y}_1 = \frac{L_1 \cos(\Theta_1)\ \dot{\Theta}_1}{2}$$

Positions and velocites of the center of mass of link 2;

$$x_2 = L_1 \cos(\Theta_1) + \frac{L_2 \cos(\Theta_2)}{2} + x_w$$

$$y_2 = \frac{L_2 \sin(\Theta_2)}{2} + L_1 \sin(\Theta_1) + y_w$$

$$\dot{x}_2 = -L_1 \sin(\Theta_1)\ \dot{\Theta}_1 - \frac{L_2 \sin(\Theta_2)\ (\dot{\Theta}_2)}{2}$$
$$\dot{y}_2 = L_1 \cos(\Theta_1)\ \dot{\Theta}_1 + \frac{L_2 \cos(\Theta_2)\ (\dot{\Theta}_2)}{2}$$

Positions and velocites of the center of mass of link 3;

$$x_3 = L_5 + \frac{L_3 \cos(\Theta_3)}{2} + L_4 \cos(\Theta_4) + x_w$$
$$y_3 = \frac{L_3 \sin(\Theta_3)}{2} + L_4 \sin(\Theta_4) + y_w$$
$$\dot{x}_3 = -\frac{L_3 \sin(\Theta_3)\ \dot{\Theta}_3}{2} - L_4 \sin(\Theta_4)\ \dot{\Theta}_4$$
$$\dot{y}_3 = \frac{L_3 \cos(\Theta_3)\ \dot{\Theta}_3}{2} + L_4 \cos(\Theta_4)\ \dot{\Theta}_4$$

Positions and velocites of the center of mass of link 4;

$$x_4 = L_5 + \frac{L_4 \cos(\Theta_4)}{2} + x_w$$
$$y_4 = \frac{L_4 \sin(\Theta_4)}{2} + y_w$$
$$\dot{x}_4 = -\frac{L_4 \sin(\Theta_4)\ \dot{\Theta}_4}{2}$$
$$\dot{y}_4 = \frac{L_4 \cos(\Theta_4)\ \dot{\Theta}_4}{2}$$

The polar form vector loop equation of the robotic five-bar mechanism given in eq. 1 is:

$$L_1 e^{i\theta_1} + L_2 e^{i\theta_2} = L_3 e^{i\theta_3} + L_5 + L_4 e^{i\theta_4} \tag{1}$$

In this system, the angular positions θ_1 and θ_4 correspond to the known input joints. The angular positions θ_2 and θ_3 can be found by solving nonlinear equations given by Eq.(1). θ_2 and θ_3 are dependent on the values of θ_1 and θ_4, and thus need to be determined based on these known input angles. The relationship between these angles can be expressed through a function $g(\theta_1, \theta_4) = (\theta_2, \theta_3)$, which gives the values of θ_2 and θ_3. Here, θ_2 and θ_3 must be determined numerically or analytically from the known input angles θ_1 and θ_4. This relationship indicates that once θ_1 and θ_4 are specified, the system can be solved for the remaining unknown angles.

$$L_1 e^{i\theta_1} + L_2 e^{i\theta_2} - L_5 - L_4 e^{i\theta_4} = L_3 e^{i\theta_3}$$
$$L_1 e^{-i\theta_1} + L_2 e^{-i\theta_2} - L_5 - L_4 e^{-i\theta_4} = L_3 e^{-i\theta_3}$$

To eliminate the unknown θ_3, both equations are multiplied;

$$\left(-L_1 e^{-i\theta_1} + L_5 + L_4 e^{-i\theta_4} + L_3 e^{-i\theta_3}\right) \cdot \left(-L_1 e^{i\theta_1} + L_5 + L_4 e^{i\theta_4} + L_3 e^{i\theta_3}\right) = L_2^2$$

Upon expanding this product, using the properties of complex numbers, the result is a real-valued equation:

$$(-L_1\cos(\theta_1) + L_5 + L_4\cos(\theta_4) + L_3\cos(\theta_3))^2 + (L_1\sin(\theta_1) - L_4\sin(\theta_4) - L_3\sin(\theta_3))^2 = L_2^2$$

To solve this equation for θ_3 using the Newton-Raphson method, we rearrange it into the following form:

$$f(\theta_3) = (-L_1\cos(\theta_1) + L_5 + L_4\cos(\theta_4) + L_3\cos(\theta_3))^2 + (L_1\sin(\theta_1) - L_4\sin(\theta_4) - L_3\sin(\theta_3))^2 - L_2^2 = 0$$

To apply the Newton-Raphson method, we first calculate the derivative of $f(\theta_3)$:

$$\frac{d}{d\theta_3}f(\theta_3) = 2(-L_1\cos(\theta_1) + L_5 + L_4\cos(\theta_4) + L_3\cos(\theta_3))(-L_3\sin(\theta_3)) + 2(L_1\sin(\theta_1) - L_4\sin(\theta_4) - L_3\sin(\theta_3))(-L_3\cos(\theta_3))$$

The Newton-Raphson iteration for θ_3 is updated as follows:

$$\theta_3^{(k+1)} = \theta_3^{(k)} - \frac{f\left(\theta_3^{(k)}\right)}{f'\left(\theta_3^{(k)}\right)}$$

This iterative process allows us to numerically find the value of θ_3 that satisfies the equation. Thus, by eliminating the imaginary components within the complex vectorial loop equation and substituting them accordingly, θ_2 can be determined.

$$\theta_2 = \cos^{-1}\left(\frac{L_5 - L_1\cos(\Theta_1) + L_3\cos(\Theta_3) + L_4\cos(\Theta_4)}{L_2}\right)$$

The derivative of the vector loop was computed, and subsequently, it was divided by its conjugate to isolate the derivative of θ_2, by eliminating the derivative of θ_3. Subsequently, it is substituted to determine the derivative of θ_3.

$$i\dot{\Theta}_1 L_1 e^{i\Theta_1} + i\dot{\Theta}_2 L_2 e^{i\Theta_2} = i\dot{\Theta}_4 L_4 e^{i\Theta_4} + i\dot{\Theta}_3 L_3 e^{i\Theta_3}$$

$$\dot{\Theta}_2 = -\frac{L_1\sin(\Theta_1-\Theta_3)\,\dot{\Theta}_1 + L_4\sin(\Theta_3-\Theta_4)\,\dot{\Theta}_4}{L_2\sin(\Theta_2-\Theta_3)},$$

$$\dot{\Theta}_3 = \frac{L_1\sin(\Theta_1)\,\dot{\Theta}_1 + L_2\sin(\Theta_2)\,\dot{\Theta}_2 - L_4\sin(\Theta_4)\,\dot{\Theta}_4}{L_3\sin(\Theta_3)}$$

To determine the accelerations, the time derivative of the vector loop in its complex form is taken once again. it was divided by its conjugate to eliminate the derivative of θ_3. After finding $\ddot{\Theta}_2$, it is substituted to determine the $\ddot{\Theta}_3$.

$$
\begin{aligned}
&iL_1\ddot{\Theta}_1e^{i\Theta_1} - L_1\dot{\Theta}_1^2e^{i\Theta_1} + iL_2\ddot{\Theta}_2e^{i\Theta_2} - L_2\dot{\Theta}_2^2e^{i\Theta_2} - iL_4\ddot{\Theta}_4e^{i\Theta_4} + L_4\dot{\Theta}_4^2e^{i\Theta_4} \\
&\qquad + L_3\dot{\Theta}_3^2e^{i\Theta_3} = iL_3\ddot{\Theta}_3e^{i\Theta_3}
\end{aligned}
$$

$$
\begin{aligned}
\ddot{\Theta}_2 = {} & \frac{L_1 \cos(\sigma_3)\ \dot{\Theta}_1{}^2 + L_1\ddot{\Theta}_1\ \sin(\sigma_3) - L_4 \cos(\sigma_1)\ \dot{\Theta}_4{}^2}{-L_2 \sin(\sigma_2)} \\
& + \frac{-L_4\ddot{\Theta}_4 \sin(\sigma_1) + L_2 \cos(\sigma_2)\ \dot{\Theta}_2{}^2 - L_3\,\dot{\Theta}_3{}^2}{-L_2 \sin(\sigma_2)}
\end{aligned}
$$

$where$

$$\sigma_1 = \Theta_4 - \Theta_3$$

$$\sigma_2 = \Theta_2 - \Theta_3$$

$$\sigma_3 = \Theta_1 - \Theta_3$$

$$
\begin{aligned}
\ddot{\Theta}_3 = {} & \frac{L_3 \sin(\Theta_3)\ \dot{\Theta}_3{}^2 - L_2 \sin(\Theta_2)\ \dot{\Theta}_2{}^2 - L_1 \sin(\Theta_1)\ \dot{\Theta}_1{}^2 + L_4 \sin(\Theta_4)\ \dot{\Theta}_4{}^2}{L_3 \cos(\Theta_3)} \\
& + \frac{L_1\,\ddot{\Theta}_1 \cos(\Theta_1) + L_2\,\ddot{\Theta}_2 \cos(\Theta_2) - L_4\,\ddot{\Theta}_4 \cos(\Theta_4)}{L_3 \cos(\Theta_3)}
\end{aligned}
$$

Since the system has two degrees of freedom (DOF), it is sufficient to derive the equations of motion only for θ_1 and θ_4. Since θ_2 and θ_3 are explicitly defined in terms of θ_1 and θ_4, the system's independent generalized coordinates are only θ_1 and θ_4. Therefore, deriving the Lagrange equations only for θ_1 and θ_4 is sufficient to fully describe the system's dynamics. Where L is the Lagrangian function and τ_i are the input torques applied to the system. Since there is no gravitational potential energy (V = 0), the Lagrangian is given solely by the total kinetic energy, where x_i and y_i are the center of mass positions of the links.

$$L = \sum_{i=1}^{4}\left[\frac{1}{2}m_i\left(\dot{x}_i^2 + \dot{y}_i^2\right) + \frac{1}{2}I_i\dot{\theta}_i^2\right]$$

$$
\begin{aligned}
L \\
= {} & \frac{m_1\left(\frac{L_1{}^2\ \cos^2(\Theta_1)\ \dot{\Theta}_1{}^2}{4} + \frac{L_1{}^2\ \sin^2(\Theta_1)\ \dot{\Theta}_1{}^2}{4}\right)}{2} + \frac{m_4\left(\frac{L_4{}^2\ \cos^2(\Theta_4)\ \dot{\Theta}_4{}^2}{4} + \frac{L_4{}^2\ \sin^2(\Theta_4)\ \dot{\Theta}_4{}^2}{4}\right)}{2} \\
& + \frac{m_2\left(\left(L_1\ \cos(\Theta_1)\ \dot{\Theta}_1 + \frac{L_2\ \cos(\Theta_1 + \Theta_2^{+})\ (\dot{\Theta}_1 + \dot{\Theta}^{+}{}_2)}{2}\right)^2 + \left(L_1\ \sin(\Theta_1)\ \dot{\Theta}_1 + \frac{L_2\ \sin(\Theta_1 + \Theta_2^{+})\ (\dot{\Theta}_1 + \dot{\Theta}^{+}{}_2)}{2}\right)^2\right)}{2} \\
& + \frac{m_3\left(\left(L_4\ \cos(\Theta_4)\ \dot{\Theta}_4 + \frac{L_3\ \cos(\Theta_3^{+} + \Theta_4)\ (\dot{\Theta}^{+}{}_3 + \dot{\Theta}_4)}{2}\right)^2 + \left(L_4\ \sin(\Theta_4)\ \dot{\Theta}_4 + \frac{L_3\ \sin(\Theta_3^{+} + \Theta_4)\ (\dot{\Theta}^{+}{}_3 + \dot{\Theta}_4)}{2}\right)^2\right)}{2} \\
& + \frac{L_1{}^2\,m_1\,\dot{\Theta}_1{}^2}{24} + \frac{L_4{}^2\,m_4\,\dot{\Theta}_4{}^2}{24} + \frac{L_2{}^2\,m_2\,(\dot{\Theta}_1 + \dot{\Theta}^{+}{}_2)^2}{24} + \frac{L_3{}^2\,m_3\,(\dot{\Theta}^{+}{}_3 + \dot{\Theta}_4)^2}{24}
\end{aligned}
$$

The equations of motion are derived from Lagrange's equation, given by:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\theta}_i}\right) - \frac{\partial L}{\partial \theta_i} = \tau_i, \quad i = 1,4$$

Applying the Lagrange equation for each generalized coordinate:

$$\tau_1 = \left(\frac{{L_1}^2 m_1}{3} + {L_1}^2 m_2 + \frac{{L_2}^2 m_2}{3} + L_1 L_2 m_2 \cos(\Theta_2^+)\right) \ddot{\Theta}_1 + \frac{m_2 {L_2}^2 \ddot{\Theta}^+{}_2}{3} + \frac{L_1 m_2 \cos(\Theta_2^+) L_2 \ddot{\Theta}^+{}_2}{2} - \frac{L_1 m_2 \sin(\Theta_2^+) L_2 {\dot{\Theta}^+{}_2}^2}{2} - L_1 m_2 \sin(\Theta_2^+) L_2 \dot{\Theta}^+{}_2 \dot{\Theta}_1$$

$$\tau_4 = \left(\frac{{L_3}^2 m_3}{3} + {L_4}^2 m_3 + \frac{{L_4}^2 m_4}{3} + L_3 L_4 m_3 \cos(\Theta_3^+)\right) \ddot{\Theta}_4 + \frac{m_3 {L_3}^2 \ddot{\Theta}^+{}_3}{3} + \frac{L_4 m_3 \cos(\Theta_3^+) L_3 \ddot{\Theta}^+{}_3}{2} - \frac{L_4 m_3 \sin(\Theta_3^+) L_3 {\dot{\Theta}^+{}_3}^2}{2} - L_4 m_3 \sin(\Theta_3^+) \dot{\Theta}_4 L_3 \dot{\Theta}^+{}_3$$

RESULTS AND DISCUSSION

The dynamic equations are implemented in the MATLAB Simulink environment, and the initial conditions of the system are defined accordingly. The mathematical model is represented using Simulink blocks, as illustrated in Figure 2. The initial joint angles θ_1 and θ_4 are set to 140° and 90°, respectively, while an initial approximate value of 114° is assigned to θ_3. Constant torque inputs of 0.1 Nm are applied to τ_1 and τ_4, and the open-loop dynamic response of the system is examined over a time interval of 1 s. The length and mass values are given respectively. $L_n = [0.4, 0.4, 0.4, 0.4]\ (m)$, $m_n = [0.95, 0.95, 0.95, 0.95]\ (kg)$, $L_5 = 0.16\ (m)$. The Runge–Kutta based ODE solver is employed, and the time step is fixed at 0.0001 sec. The time evolution of the joint angles, representing the open-loop system dynamics, is presented in Figures 3 and 4. These observations establish a reference framework for evaluating the intrinsic dynamic characteristics of the system and serve as a basis for subsequent control design and performance assessment.

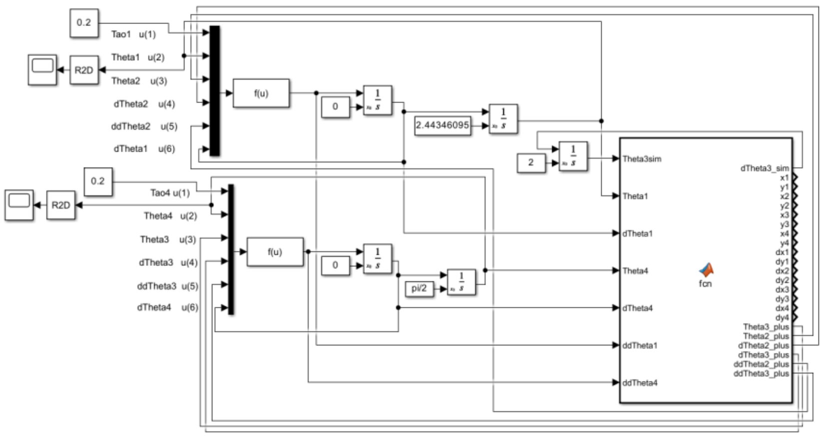

Figure 2. Block diagram of mathematical model

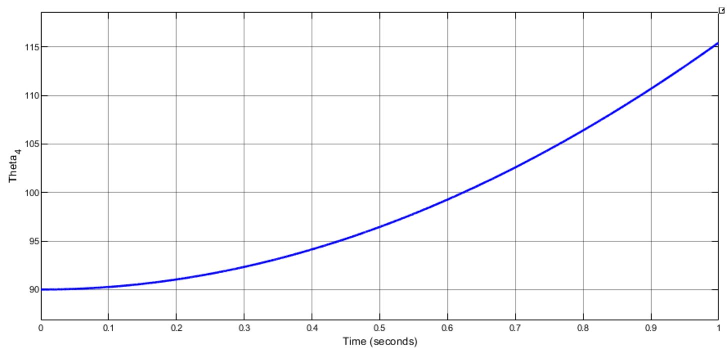

Figure 3. The time response of θ_4 over a 1 second interval

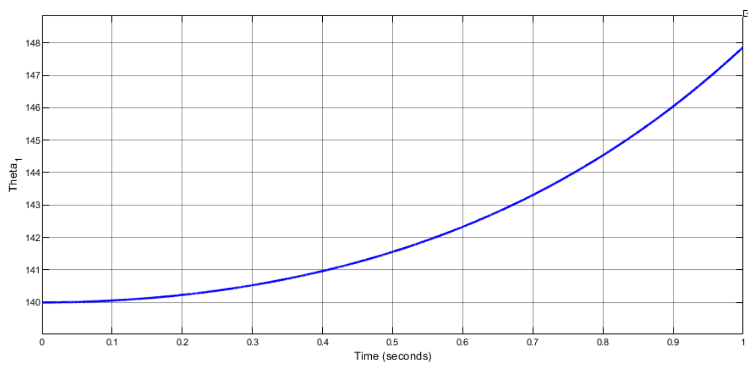

Figure 4. The time response of θ_1 over a 1 second interval

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How 3D Printing Is Revolutionizing Battery Technology

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ABSTRACT

3D printing is revolutionizing battery technology by eliminating the constraints of traditional manufacturing methods. It enables the production of batteries in virtually any shape, allowing seamless integration into modern electronic devices. This flexibility is especially valuable for compact and wearable technologies, where space optimization is critical. More importantly, 3D printing offers precise control over a battery's internal structure. Engineers can design intricate architectures that improve ion and electron transport, resulting in batteries with significantly enhanced energy and power density. This structural customization opens the door to high-performance energy storage solutions tailored to specific applications. Additionally, the rapid prototyping capabilities of 3D printing accelerate innovation. Researchers can quickly test new materials and configurations, shorten development cycles and reduce costs. This agility fosters experimentation and speeds up the transition from concept to commercial product. Overall, 3D printing is ushering in a new era of battery design—one that prioritizes performance, adaptability, and integration. As technology matures, it promises to deliver energy storage systems that are not only more efficient but also better suited to the evolving demands of next-generation electronics.

Keywords – 3D printing; battery architecture; energy density; rapid prototyping; integration.

INTRODUCTION

For decades, the batteries that power our world have been confined to rigid, standardized shapes—cylinders, pouches, and rectangular prisms. While functional, these "brick" batteries severely restrict the design of modern electronics. Devices like wearable health monitors, smart sensors, and medical implants are forced to conform to the battery's shape, not the other way around (Fonseca et al., 2023). This limitation often leads to inefficient use of space and compromises in device form and function.

Enter 3D printing, also known as additive manufacturing. This groundbreaking technology offers a powerful solution by freeing batteries from their geometric constraints. 3D printing enables the creation of custom-shaped batteries that can be perfectly integrated into any device, unlocking new design possibilities and enhanced performance (Lyu et al., 2021). This document explains in simple terms how 3D printing works, how it is used to build the essential components of a battery, and why this represents a true revolution in energy storage. But before we can understand how to print a battery, we first need to know what a battery is made of.

1. Battery 101: The Three Key Ingredients

At its core, a battery is a device that stores chemical energy and converts it into electrical energy through an electrochemical process. The operation of a modern lithium-ion battery depends on three essential components, which can be thought of as a sandwich: two "bread" slices (the electrodes) with a "filling" (the electrolyte) in between. During charging and discharging, tiny charged particles called ions travel through the electrolyte from one electrode to the other (Maurel et al., 2023; Pavlovskii et al., 2024). The table below outlines the function of these three key ingredients.

Table 1. The function of these three key ingredients: Anode, cathode, electrolyte

Component	Function
Anode	The negative electrode. It *stores* lithium ions when the battery is charged and releases them during use.
Cathode	The positive electrode. During use (discharging), it *receives* ions from the anode. When the battery is plugged in (charging), it *releases* the ions back.
Electrolyte	A chemical medium that allows ions to travel between the anode and cathode but blocks the flow of electrons, forcing them through an external circuit to power a device.

To prevent the anode and cathode from touching—which would cause a dangerous short circuit—a thin, porous membrane called a **separator** is placed between them. This separator acts as a physical barrier that only allows ions to pass through (Hu et al., 2021, as cited in Liu et al., 2021).

Now that we understand the basic building blocks of a battery, let's explore the technology that allows us to construct them layer by layer.

2. 3D Printing 101: Building from the Ground Up

3D printing, or additive manufacturing, is a process that builds three-dimensional objects layer-by-layer from a digital design file (Tian et al., 2017). This is fundamentally different from traditional "subtractive" manufacturing.

- **Additive Manufacturing (3D Printing):** Imagine building a sculpture by adding small pieces of clay one by one until the final form is complete.
- **Subtractive Manufacturing:** This is like carving a sculpture from a solid block of stone, where you remove material to reveal the final shape.

This layer-by-layer approach gives designers incredible freedom to create complex shapes and internal structures that are difficult or impossible to make with conventional methods (Lyu et al., 2021). While there are many ways to 3D print, a few key methods have proven especially powerful for creating the next generation of batteries.

3. A Tour of 3D Printing Methods for Batteries

Different 3D printing methods are suited for different materials and battery components. Each technique offers a unique set of advantages, from high resolution to material versatility. Below is an overview of the most common methods used in battery manufacturing.

3.1. Direct Ink Writing (DIW)

DIW is an extrusion-based method where a viscous, paste-like "ink" is precisely dispensed through a fine nozzle to draw a structure layer by layer (Deivanayagam et al., 2020; Tian et al., 2017). The ink is a **shear-thinning** material, meaning it flows easily like a liquid when under pressure but immediately holds its shape like a solid once deposited (Deivanayagam et al., 2020).

- **Material Type:** Viscous liquid ink (polymers, ceramics, composites).
- **Primary Benefit:** DIW is the most common method for printing battery components due to its exceptional versatility with a wide range of materials (Xue et al., 2024).

3.2. Fused Deposition Modeling (FDM)

FDM is another extrusion method, but it uses a solid thermoplastic filament instead of a liquid ink. The filament is fed into a heated nozzle, where it melts and is deposited onto a platform; it then cools and solidifies to form a layer (Chu et al., 2021). To create battery components, the plastic filament (e.g., PLA) must be pre-mixed with conductive and active materials, such as graphene or lithium iron phosphate (LiFePO4) (Maurel et al., 2023).

- **Material Type:** Solid thermoplastic filament.
- **Primary Benefit:** This method is effective at creating durable, free-standing electrode structures. However, a key challenge is loading enough active material into the filament for good battery performance without making it too brittle to print (Egorov et al., 2020).

3.3. Inkjet Printing (IJP)

Similar to a desktop paper printer, IJP works by depositing tiny droplets of a low-viscosity liquid ink onto a substrate to build up layers (Pavlovskii et al., 2024). The ink's physical properties, such as viscosity and surface tension, are critical to ensure stable and precise droplet formation (Wang et al., 2023).

- **Material Type:** Low-viscosity liquid ink.
- **Primary Benefit:** IJP is ideal for creating extremely thin and precise layers, making it perfect for fabricating thin-film electrodes or microbatteries (Liu et al., 2021).

3.4. Stereolithography (SLA)

SLA is a vat photopolymerization technique. It uses an ultraviolet (UV) laser to selectively trace a pattern onto the surface of a liquid photocurable resin, causing it to cure and solidify. The platform then moves, and the process repeats for the next layer (Chu et al., 2021; Deivanayagam et al., 2020). For battery applications, active materials are mixed directly into the liquid resin.

- **Material Type:** Liquid photocurable resin.
- **Primary Benefit:** SLA can produce structures with very high resolution and intricate geometries, making it ideal for creating complex electrolyte architectures or finely detailed electrode scaffolds (Pavlovskii et al., 2024).

3.5. Selective Laser Sintering (SLS)

SLS is a powder bed fusion technique. It uses a high-power laser to selectively fuse, or sinter, particles of a powder (such as metal or polymer) together, layer by layer (Deivanayagam et al., 2020).

- **Material Type:** Fine powder (metal or polymer).
- **Primary Benefit:** Its key advantage is the ability to directly print metal components without needing binders. This makes it highly useful for creating porous metal current collectors that provide structural support and electrical conductivity for the electrodes (Liu et al., 2021).

With these powerful techniques, scientists and engineers are now able to construct every part of a battery with unprecedented control, leading to major breakthroughs.

4. The Revolution: Printing a Better Battery

By allowing for the precise fabrication of each individual component, 3D printing offers significant advantages over the rigid, one-size-fits-all approach of traditional battery manufacturing.

4.1. Building a Battery, Piece by Piece

3D printing can be used to create every core component of a battery with custom designs and materials.

- **Printing Electrodes (Anodes & Cathodes):** This is the most developed application of 3D printing in battery manufacturing. Direct Ink Writing (DIW) is commonly used to print inks that contain active materials like LiFePO4 (LFP) for the cathode and Li4Ti5O12 (LTO) for the anode.

These materials are often mixed with conductive additives like graphene oxide to create stable, high-performance electrodes (Fu et al., 2016).

- **Printing Electrolytes:** 3D printing is critical for advancing solid-state and gel polymer electrolytes, which are safer than traditional liquid electrolytes. For instance, Stereolithography (SLA) can be used to create complex, zig-zag shaped gel polymer electrolytes. This intricate shape dramatically increases the contact area between the electrode and the electrolyte, which improves the flow of ions and boosts battery performance (Chen et al., 2017; Zekoll et al., 2018).
- **Printing Separators and Current Collectors:** Other essential components can also be printed. Selective Laser Sintering (SLS) can create highly porous stainless steel current collectors that provide excellent electrical contact (Wu et al., 2021, as cited in Liu et al., 2021), while DIW can fabricate thermally stable separators from advanced materials like boron nitride to enhance safety (Hu et al., 2021, as cited in Liu et al., 2021).

4.2. Key Advantages of a Printed Battery

Synthesizing these capabilities reveals three transformative advantages that 3D-printed batteries have over their conventional counterparts.

- **Custom Shapes for Perfect Integration** Batteries no longer need to be rectangular. They can be printed in complex, freeform shapes to fit perfectly inside devices like wearable sensors, medical implants, or smart clothing. This maximizes the use of internal space, leading to smaller devices or longer battery life (Fonseca et al., 2023; Lyu et al., 2021).
- **Superior Performance by Design** 3D printing allows for the creation of intricate internal architectures that are precisely engineered to boost battery performance in ways that are impossible with traditional slurry-casting methods.
- **Higher Power:** To achieve faster charging and discharging, designers can print **interdigitated electrodes**—microscopic, interlocking "fingers" of anode and cathode. This architecture drastically shortens the distance ions need to travel, enabling much higher power output (Sun et al., 2013; Xue & He, 2022).
- **Higher Energy:** To store more energy in the same footprint, designers can print **3D lattice structures**. These create highly ordered, porous electrodes with low tortuosity (i.e., less twisted paths for ions). This design allows for much thicker electrodes to be made without sacrificing performance, which significantly increases the total amount of energy the battery can store (Lyu et al., 2021; Wei et al., 2018).
- **Accelerated Innovation and Development** 3D printing enables rapid prototyping. Engineers can design a new battery concept in software, print a physical prototype, and begin testing it in a fraction of the time and cost required for traditional manufacturing. This ability to quickly iterate on

new designs dramatically speeds up the discovery and development of new and better battery technologies (Fonseca et al., 2023; Gulzar et al., 2020).

These profound advantages demonstrate that 3D printing is not just an alternative manufacturing method but a transformative force in energy storage.

RESULTS AND DISCUSSION

3D printing is fundamentally reshaping the landscape of battery technology by overcoming the long-standing limitations of conventional manufacturing. By enabling the creation of batteries in virtually any shape, this technology allows for seamless integration into the next generation of electronics.

More importantly, 3D printing provides unprecedented control over a battery's internal architecture. By designing structures that enhance ion and electron transport, it is possible to create batteries with significantly higher energy and power density. Combined with the ability to rapidly prototype and test new ideas, 3D printing is paving the way for a new era of high-performance, fully integrated energy storage devices that will power the future of technology.

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Energy Storage Technology With 3D Printing Technology: A Glimpse Into The Future Of Batteries

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ABSTRACT

This section emphasizes the transformative role of 3D printing in advancing electrochemical energy storage devices (EESDs). Unlike traditional manufacturing methods such as slurry-casting and stacking, 3D printing offers unmatched design flexibility, enabling the creation of complex internal architectures like low-tortuosity frameworks, interdigitated micro-electrodes, and porous scaffolds. These structures significantly improve ion and electron transport, especially in thick electrodes used for high-energy applications. As a result, 3D-printed batteries can achieve better rate capability, higher areal capacity, and longer cycle life—demonstrating the critical value of architectural control. Despite its promise in research environments, the commercial adoption of 3D-printed EESDs faces challenges. Key obstacles include the development of materials that are both electrochemically efficient and suitable for printing, as well as issues related to scalability and integration of multiple components. However, ongoing progress in multi-material printing, computational design, and sustainable feedstocks is rapidly addressing these barriers. With these advancements, 3D printing is poised to become a foundational technology for producing next-generation energy storage systems that are not only high-performing and safe but also customizable to specific application needs.

Keywords – 3D printing; electrochemical energy storage device; architectural control; material compatibility; scalability.

INTRODUCTION

1. Revolutionizing Energy Storage with Additive Manufacturing

Electrochemical energy storage devices (EESDs), such as lithium-ion batteries and supercapacitors, are foundational technologies in the global transition toward renewable energy and portable electronics (Zhu et al., 2017). However, the performance and design flexibility of these devices are often constrained by the limitations of conventional manufacturing. Traditional methods like slurry casting, tape-casting, and layer-by-layer stacking impose significant restrictions on battery dimensions, functionalities, and architectures (Fonseca et al., 2023; Maurel et al., 2023). These planar fabrication techniques are particularly problematic for producing thick electrodes, which are necessary for high energy density. In thick electrodes, the convoluted and random pore structures result in high tortuosity, which significantly impedes ion transport, increases internal resistance, and ultimately lowers the device's power density (Chu et al., 2021; Xue et al., 2022).

In response to these challenges, 3D printing, also known as additive manufacturing (AM), has emerged as a transformative approach to fabricating next-generation EESDs. Unlike subtractive manufacturing, AM builds three-dimensional objects layer-by-layer from a digital model, offering unparalleled design freedom (Fonseca et al., 2023). This capability allows for the creation of EESDs with rationally designed, complex architectures that are simply unachievable with conventional methods. The core value proposition of 3D printing lies in its ability to optimize device performance through structural control, enhance material and cost efficiency by minimizing waste, and accelerate innovation through rapid prototyping (Lyu et al., 2021; Tian et al., 2017). By enabling the fabrication of electrodes with low-tortuosity pathways, interdigitated designs, and high-surface-area scaffolds, 3D printing directly addresses the transport limitations in thick electrodes, paving the way for devices with simultaneously high energy and power densities (Lyu et al., 2021).

This review provides a comprehensive technical analysis of the current state of 3D printing for EESDs. It evaluates the primary printing techniques, materials, and advanced architectures being employed to fabricate high-performance batteries and supercapacitors. Furthermore, it examines the key challenges that must be overcome for widespread adoption and discusses the future outlook for this promising manufacturing paradigm.

2. A Comparative Analysis of 3D Printing Techniques for EESDs

The selection of an appropriate 3D printing technique is a strategic decision that fundamentally dictates the properties and performance of the resulting EESD. Each method offers a unique combination of advantages and limitations, and the optimal choice depends on a range of factors, including the type of material to be printed (e.g., polymer, ceramic, composite), the required resolution and structural complexity, manufacturing speed, and overall cost (Ma et al., 2024). The suitability of a technique is also component-specific; for instance, a method ideal for fabricating a porous electrode may be unsuitable for a dense solid-state electrolyte. This section provides a detailed comparative analysis of the most prominent 3D printing techniques used in EESD fabrication, highlighting their principles, material requirements, and specific strengths and weaknesses in this application.

2.1. Direct Ink Writing (DIW)

Direct Ink Writing (DIW) is a material extrusion method wherein a viscoelastic ink is dispensed through a micro-nozzle to build a 3D structure layer-by-layer (Deivanayagam et al., 2020). This technique is currently the most common method for fabricating EESDs due to its material versatility and ability to create complex 3D architectures (Xue et al., 2024).

The success of DIW is critically dependent on the rheological properties of the ink. Ideal inks exhibit shear-thinning behavior, where viscosity decreases under the high shear stress applied during extrusion, allowing the material to flow smoothly through the nozzle. Upon deposition, the shear stress is removed, and the ink's viscosity rapidly recovers, enabling it to retain its shape and support subsequent layers (Deivanayagam et al., 2020). This behavior is often described by the Herschel-Bulkley model, $\tau = \tau y + K\dot{\gamma}^n$, where τ is the shear stress, τy is the yield stress that must be overcome for flow to begin, and $n < 1$ indicates shear-thinning (Chen et al., 2024; Liu et al., 2021). The primary strength of DIW is its exceptional material flexibility, accommodating a wide range of inks including ceramics, polymers, hydrogels, and composites like graphene oxide (GO), which is often used to tune the ink's rheology (Fu et al., 2016; Deivanayagam et al., 2020). However, a key limitation is the frequent need for rheological additives and binders, which are often not electrochemically active and can consequently reduce the final device's energy density and mechanical integrity (Liu et al., 2021; Ma et al., 2024).

2.2. Fused Deposition Modeling (FDM)/Fused Filament Fabrication (FFF)

Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF), is an extrusion-based technique that constructs objects by melting a thermoplastic filament and depositing it onto a substrate layer-by-layer, where it cools and solidifies (Chu et al., 2021). FDM is one of the most accessible and low-cost 3D printing methods, making it attractive for rapid prototyping (Hosseini et al., 2024).

For EESD applications, the filament is a composite, typically made of a thermoplastic polymer like polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) loaded with electrochemically active materials (e.g., $LiFePO_4$ (LFP), graphite) and conductive additives (e.g., graphene, carbon black) (Maurel et al., 2023; Pavlovskii et al., 2024). The primary challenge of FDM for EESDs is the low electrical conductivity of the final printed part. This is due to the high volume percentage of the insulating thermoplastic binder required to make the filament printable, which can isolate the active particles and impede electron transport (Gulzar et al., 2020; Egorov et al., 2020). Researchers have explored strategies to mitigate this, such as increasing the loading of conductive fillers and applying post-processing treatments. For example, treating a printed PLA/graphene electrode with sodium hydroxide (NaOH) can create microporosity, enhancing electrolyte infiltration and dramatically increasing specific capacity (Fonseca et al., 2023). Despite conductivity challenges, FDM's key advantages remain its low cost, widespread availability, and the excellent mechanical properties of the printed components (Hosseini et al., 2024).

2.3. Inkjet Printing (IJP)

Inkjet Printing (IJP) is a material jetting technique that creates patterns and layers by depositing picoliter-sized droplets of ink onto a substrate (Ma et al., 2024). This method is renowned for its high precision and ability to control material deposition with exceptional accuracy.

The applicability of IJP is constrained by stringent ink property requirements. For stable droplet formation and ejection, the ink must have a very low viscosity and specific surface tension, a relationship often characterized by the inverse Ohnesorge number (Z), which should typically fall between 1 and 10 (Ansari et al., 2023; Ma et al., 2024). This low viscosity requirement limits the loading of active materials and makes IJP best suited for fabricating thin-film components, such as electrodes or electrolytes, rather than self-standing 3D structures (Pinilla, 2024). The main advantages of IJP are its high resolution, non-contact nature, and precise material deposition, which significantly reduces material waste and cost (Hosseini et al., 2024). However, its primary drawbacks for EESD fabrication include the difficulty of building thick, 3D configurations due to the ink's lack of self-supporting ability and the potential for nozzle clogging, especially with particle-based inks (Liu et al., 2021; Pinilla, 2024).

2.4. Stereolithography (SLA)

Stereolithography (SLA) is a vat photopolymerization technique that builds objects by selectively curing a liquid photocurable resin with a focused light source, typically an ultraviolet (UV) laser, in a layer-by-layer fashion (Deivanayagam et al., 2020).

The material palette for SLA is limited to photocurable polymer resins. To fabricate EESD components, active and conductive materials must be dispersed within this resin. This presents a significant challenge, as the cured polymer matrix is typically electrically insulating, which can hinder the electrochemical performance of the final device (Chu et al., 2021; Gao et al., 2024). The standout advantage of SLA is its ability to produce parts with exceptionally high resolution (as fine as 0.5 μm) and create truly arbitrary and complex 3D geometries, as its design freedom is not constrained by a physical toolpath like extrusion methods (Deivanayagam et al., 2020; Xue et al., 2024). Key limitations include the restricted material selection, the necessity for post-processing steps to remove uncured resin, and the potential for residual non-active polymer to compromise the device's electrochemical performance and stability (Ansari et al., 2023; Xue et al., 2024).

2.5. Summary and Comparison

The selection of a 3D printing technique is a critical step that involves trade-offs between resolution, material compatibility, cost, and structural complexity. The table below synthesizes the key characteristics of the discussed methods, along with Selective Laser Sintering (SLS), to provide a comparative overview for EESD applications. While this comparison highlights the distinct capabilities of each method, their true impact is realized in the fabrication of advanced three-dimensional architectures. The high resolution of SLA, for instance, is critical for creating intricate gyroidal electrolytes, while the material versatility of DIW makes it the leading choice for printing low-tortuosity lattice electrodes, as will be explored in the following section.

Table 1. The key characteristics of the discussed methods (Data synthesized from: Ansari et al., 2023; Deivanayagam et al., 2020; Egorov et al., 2020; Hosseini et al., 2024; Liu et al., 2021; Ma et al., 2024; Xue et al., 2024)

Printing Technique	Principle	Typical Materials	Resolution	Key Advantages for EESDs	Key Limitations for EESDs
Direct Ink Writing (DIW)	Extrusion of a viscoelastic ink through a nozzle.	Ceramics, polymers, gels, metal composites, graphene oxide inks.	1–250 µm	High material versatility, enables complex 3D architectures, most common method for EESDs.	Requires additives that can reduce electrochemical performance; potential mechanical property limitations.
Fused Deposition Modeling (FDM)	Extrusion of a heated thermoplastic filament.	Thermoplastics (PLA, ABS) loaded with active and conductive materials.	50–400 µm	Low cost, accessibility, good mechanical properties, minimal material waste.	Low electrical conductivity due to insulating polymer binder; limited precision and material range.
Inkjet Printing (IJP)	Deposition of picoliter-sized ink droplets.	Low-viscosity inks containing nanoparticles (graphene, Si, LTO).	10–150 µm	High resolution, precise material deposition (reduces waste), suitable for thin films.	Difficult to build 3D structures; strict ink viscosity requirements; potential nozzle clogging.
Stereolithography (SLA)	Selective curing of a liquid photopolymer resin using a light source.	Photocurable resins (e.g., PEGDA) with dispersed active materials.	0.5–30 µm	Very high resolution, enables fabrication of highly complex and arbitrary geometries.	Limited material selection (must be photocurable); residual polymer can impair performance; requires post-processing.
Selective Laser Sintering (SLS)	Fusing layers of powdered material using a high-power laser.	Thermally fusible powders (polymers, metals, ceramics, carbon composites).	0.5–20 µm	Can directly print metal components (e.g., current collectors); wide material variety without ink/resin constraints.	High equipment cost; rough surface finish; can result in porous, weak parts without post-processing.

3. 3D-Printed Architectures and Components for High-Performance EESDs

The true transformative power of 3D printing in energy storage lies not just in replicating existing components but in its ability to fabricate EESD components with rationally designed, three-dimensional architectures. Conventional manufacturing is largely confined to simple, planar structures, which leads to well-known performance trade-offs, especially in thick electrodes where long, tortuous ion pathways limit power output (Chu et al., 2021). 3D printing breaks this paradigm by enabling the creation of structures engineered to optimize ion and electron transport, maximize active material loading, and improve mechanical stability under cycling. These advanced architectures directly impact key performance metrics, unlocking new possibilities for customized, high-performance energy storage solutions. The following sections explore how these architectural innovations are being applied to fabricate the key components of a battery.

3.1. Advanced Electrode Architectures

The electrode is arguably the most critical component of an EESD, and its internal structure dictates the device's energy and power capabilities. 3D printing enables the design of advanced electrode architectures that overcome the inherent limitations of traditional slurry-cast films.

• **Low-Tortuosity Structures**: Traditional thick electrodes are characterized by a random, convoluted network of pores, creating a highly tortuous path for ion transport. This high tortuosity increases the effective path length ions must travel, leading to higher internal resistance and lower power density (Chu et al., 2021). 3D printing allows for the fabrication of electrodes with ordered, low-tortuosity structures, such as microlattices and hierarchical porous frameworks, most commonly achieved via DIW (Xue et al., 2022). These designs create direct, vertically aligned channels that shorten the ion diffusion distance, facilitate electrolyte penetration, and dramatically improve rate capability, even at high mass loadings (Chu et al., 2021; Lyu et al., 2021).

• **Interdigitated Structures**: This architecture involves printing the anode and cathode as a set of interlocking, finger-like electrodes on the same plane. This design drastically shortens the ion diffusion distance between the two electrodes, making it an ideal configuration for micro-batteries and supercapacitors where high rate performance is critical (Deivanayagam et al., 2020). This architecture is most effectively realized using high-resolution methods like DIW and IJP, which allow for the precise deposition of fine, interlocking features essential for micro-battery performance. The pioneering work by Sun et al. (2013) demonstrated the fabrication of interdigitated Li-ion micro-batteries using DIW, showcasing the potential of this architecture to achieve high areal energy and power densities (Liu et al., 2021).

• **3D Scaffolds and Aerogels**: Highly porous 3D scaffolds and aerogels serve as lightweight, conductive frameworks for hosting active materials. These structures offer an extremely high surface area for electrochemical reactions, enhance electrolyte infiltration, and provide mechanical support (Deivanayagam et al., 2020). For anode materials like silicon, which undergo massive volume expansion (>300%) during cycling, 3D-printed porous scaffolds provide the necessary void space to accommodate this change, preventing electrode pulverization and improving cycle life (Chen et al., 2024). Graphene aerogels, for instance, have been printed via DIW to create supercapacitor electrodes with excellent rate capability and capacitance retention (Deivanayagam et al., 2020; Tetik et al., 2021).

The implementation of these architectures has led to quantifiable performance improvements, including:

• Increased areal energy density to 9.7 J cm^{-2} in interdigitated micro-batteries (Liu et al., 2021).

• High-capacity retention of 85% over 3000 cycles at a high 10C rate in cellulose nanofiber-based electrodes, attributed to lowered local current density and improved ion accessibility (Putri et al., 2024).

• Areal capacity of 14.6 mAh cm^{-2} in a Li-O_2 battery using an ultrathick r-GO/Ni 3D scaffold (Deivanayagam et al., 2020).

3.2. Fabrication of Key Components

Beyond abstract architecture, 3D printing is being actively used to manufacture the full suite of components required for a functional battery, from electrodes and electrolytes to packaging and integrated systems.

3.2.1. Cathodes and Anodes

A wide range of common cathode materials has been successfully fabricated using 3D printing. Materials such as Lithium Iron Phosphate (LFP), Lithium Titanate (LTO), and Lithium Cobalt Oxide (LCO) are frequently formulated into printable inks or filaments. The ability to print electrodes with controlled porosity and architecture has led to significant performance gains. For instance, a 3D-printed porous LFP electrode achieved a specific capacity of 121.7 mAh·g^{-1} at a 0.5 C rate with a high active material loading of 15.9 mg·cm^{-1} (Chen et al., 2024), demonstrating the potential to create thick, high-energy-density cathodes without sacrificing rate performance.

For anodes, research has focused on carbon-based materials like graphite and graphene, which are favored for their conductivity and compatibility with various printing methods (Fonseca et al., 2023). A major area of advancement is the printing of silicon (Si) anodes. While silicon offers a very high theoretical capacity, it suffers from massive volume expansion during cycling, which typically leads to rapid degradation. 3D printing addresses this challenge by creating porous scaffolds and low-tortuosity structures that provide the necessary void space to accommodate this volumetric change. This architectural control helps maintain the electrode's structural integrity, prevent pulverization, and enable stable long-term cycling (Chen et al., 2024).

The versatility of 3D printing has enabled the application of these printed electrodes in a diverse array of next-generation battery systems. Beyond conventional Li-ion batteries, printed cathodes and anodes are being investigated for Na-ion, Zn-ion, and Li-S batteries. In Li-S systems, for example, 3D-printed porous carbon hosts are particularly effective at trapping intermediate polysulfides, a primary cause of capacity fade, thereby improving the cycle life and stability of this high-energy chemistry (Liu et al., 2021; Xue et al., 2024).

3.2.2. Electrolytes and Separators

The development of printable electrolytes, particularly solid-state electrolytes, is a critical step toward creating safer, all-solid-state batteries.

• **Solid Electrolytes**: Significant progress has been made in printing Solid Polymer Electrolytes (SPEs) and Composite Solid Electrolytes (CSEs). Materials like Poly(ethylene oxide) (PEO) are commonly used as the polymer host, with inorganic ceramic fillers such as $Li_7La_3Zr_2O_{12}$ (LLZO) or $Li_{14}Al_{04}Ge_{16}(PO_4)_3$ (LAGP) added to enhance ionic conductivity and mechanical strength (Fonseca et al., 2023; Huang et al., 2023).

• **Electrolyte Architectures**: 3D printing allows for the fabrication of electrolytes with complex, performance-enhancing geometries. For example, Chen et al. (2017) used SLA to create a zig-zag gel polymer electrolyte structure that increased the electrode-electrolyte contact area (Liu et al., 2021). Similarly, Zekoll et al. (2018) fabricated bicontinuous gyroidal structures of LAGP ceramic, creating continuous, low-tortuosity pathways for ion transport that resulted in high ionic conductivity (Deivanayagam et al., 2020).

• **Separators**: 3D printing has also been used to create customized separators. For instance, an ink containing boron nitride (BN) nanosheets was used to print a separator with excellent thermal stability and electrical insulation, improving the safety of lithium metal batteries (Liu et al., 2021).

3.2.3. Current Collectors, Packaging, and Integrated Systems

3D printing offers a holistic approach to device fabrication, extending to the non-active components that are essential for a complete and functional EESD.

• **Current Collectors**: Instead of using conventional planar foils, researchers have printed 3D scaffolds from materials like stainless steel. These 3D current collectors increase the available surface area for active material deposition and shorten electron transport pathways (Liu et al., 2021).

• **Packaging**: FDM is commonly used to fabricate customized and conformal packaging and enclosures from polymers like PLA and PVDF. This capability simplifies the final assembly process and enables the creation of batteries in non-planar or application-specific form factors (Liu et al., 2021; Maurel et al., 2023).

• **Integrated Systems**: A key advantage of 3D printing is the potential for monolithic integration. This involves co-fabricating an EESD directly with other electronic components. Examples include printing a battery and sensors together on a circuit board or integrating a supercapacitor, solar cells, and LEDs onto a T-shirt to create a self-powering wearable system (Liu et al., 2021).

4. Key Challenges and Future Outlook

Despite significant progress and compelling demonstrations of 3D-printed EESDs in laboratory settings, the technology is still in a nascent stage of development. Several formidable challenges related to materials, process control, and scalability must be addressed before 3D printing can be considered a viable, widespread commercial manufacturing method for energy storage. This section outlines the primary barriers currently impeding commercialization and explores the promising future research directions that could unlock the full potential of this technology.

4.1. Current Challenges and Commercialization Barriers

For 3D printing to transition from research to industry, the following critical challenges must be overcome:

• **Material Limitations**: The development of materials that are simultaneously high-performing electrochemically and compatible with 3D printing processes remains a major hurdle. For extrusion-based methods like FDM and SLA, the polymer binders are often electrically insulated, which compromises device performance (Fonseca et al., 2023). For ink-based methods like DIW and IJP, the stringent rheological requirements (e.g., viscosity, shear-thinning behavior) severely limit the types and concentrations of active materials that can be used (Zhu et al., 2017; Liu et al., 2021).

• **Process Control and Resolution**: There is an inherent trade-off between printing speed, resolution, and manufacturing cost. High-resolution techniques such as SLA are typically slow and may not be suitable for large-scale production, while faster methods like FDM often suffer from lower accuracy and resolution (Fonseca et al., 2023). Achieving micron-scale features consistently and rapidly is a significant manufacturing challenge.

- **Post-Processing Requirements**: Most 3D-printed EESD components are not ready for use immediately after printing. They often require subsequent processing steps such as solvent drying, binder removal, thermal annealing, or sintering to achieve the desired electrochemical and mechanical properties (Lyu et al., 2021). These additional steps add complexity, time, and cost to the overall manufacturing workflow, diminishing some of the advantages of rapid prototyping (Fonseca et al., 2023).
- **Scalability and Integration**: Translating laboratory-scale prototypes into large-scale, reproducible industrial production is a formidable challenge. Furthermore, the goal of printing an entire multi-component device (anode, cathode, electrolyte, and packaging) in a single, seamless, and automated process is still far from reality. Most current research focuses on printing individual components, which still require manual assembly (Zhu et al., 2017; Fonseca et al., 2023).

4.2. Future Research Directions and Perspectives

The continued advancement of 3D printing for EESDs will be driven by innovation in materials, printing processes, and system design. Key future directions include:

- **Multi-Material and Multi-Process Printing**: The development of advanced printing systems capable of depositing multiple materials simultaneously or combining different printing techniques (e.g., DIW for electrodes and FDM for packaging) is a critical next step. This would enable the fabrication of a complete, fully integrated battery in a single manufacturing run, eliminating the need for manual assembly and paving the way for true automated production (Fonseca et al., 2023; Zhu et al., 2017).
- **4D Printing**: This emerging concept involves 3D printing objects with "smart" materials that can change their shape, properties, or functionality over time in response to an external stimulus like heat, light, or moisture (Lyu et al., 2021). For batteries, 4D printing could be used to create structures that dynamically adapt to accommodate the large volume changes of electrodes (e.g., silicon anodes) during cycling, thereby enhancing durability and lifespan (Fonseca et al., 2023).
- **Advanced Computational Tools**: The integration of computational modeling, simulation (e.g., CFD, FEM), Artificial Intelligence (AI), and Machine Learning (ML) will accelerate progress. These tools can be used to predict the performance of novel architectures, optimize ink formulations and printing parameters, and rapidly screen new materials, significantly reducing the time and cost associated with experimental trial-and-error (Fonseca et al., 2023; Xue et al., 2022).

• **Sustainable and Green Manufacturing**: 3D printing inherently offers sustainability benefits by reducing material waste compared to subtractive methods. Future research will likely focus on developing printable EESDs from environmentally friendly and biodegradable materials, such as cellulose and PLA, contributing to a more sustainable battery life cycle from production to disposal (Fonseca et al., 2023; Huang et al., 2023).

RESULTS AND DISCUSSION

This review has highlighted the transformative potential of 3D printing as a paradigm-shifting manufacturing platform for electrochemical energy storage devices. By offering unprecedented design freedom, additive manufacturing enables the fabrication of EESDs with complex, rationally designed architectures that are unattainable through conventional slurry-casting and stacking methods. These advanced structures—including low-tortuosity frameworks, interdigitated micro-electrodes, and porous scaffolds—directly address the fundamental limitations of ion and electron transport, particularly in the thick electrodes required for high-energy applications. The resulting performance enhancements, such as improved rate capability, higher areal capacity, and extended cycle life, underscore the significant value of architectural control.

While technology has demonstrated immense promise in research settings, its transition to widespread commercial application is contingent upon overcoming significant hurdles in material development, process scalability, and multi-component integration. The need for materials that are both electrochemically superior and rheologically compatible with printing processes remains a primary challenge. Nevertheless, as advancements in multi-material printing, computational design tools, and sustainable feedstocks continue to accelerate, 3D printing is firmly positioned to become an essential technology for manufacturing the next generation of customized, safe, and high-performance energy storage devices.

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Energy Technologies of Boron

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ABSTRACT

Overuse of fossil fuels has inevitably led to problems with resources and the environment in recent decades. Instead of using fossil fuels to produce energy, new techniques and technologies are being developed to produce cleaner energy from boron through fusion, hydrolysis, and combustion nowadays. The hydrogen–boron (H–B11), also known as proton boron (p–B11) fusion reaction is a most promising choice for large–scale energy production in an attempt to restrict the future use of climate–impacting fossil fuels. The p–B11 fusion process is particularly promising for controlled nuclear fusion in energy generation. It has a nearly infinite supply of reactants on Earth for fuel, yet its primary reaction only yields three charged alpha particles rather than neutrons. The p–B11 fusion reaction is especially appealing for developing high–intensity high–energy alpha sources to create radioisotopes for medicinal uses. Because it is a nuclear process, it has an energy density that is about seven orders of magnitude more than that of chemical processes. It has an aneutronic primary reaction and does not cause material activation, which results in very little radioactive waste. The hydrolysis of boron can be utilized as a method for hydrogen production. Due to its low molecular weight and relatively high valence, boron offers distinct advantages over other metals in hydrogen generation, particularly for transportation applications. The oxide byproduct formed during this process can be reduced, enabling the recovery of elemental boron through established techniques, either via chemical reduction with magnesium or by electrolysis. Under specific conditions, boron exhibits high flammability and explosive characteristics. Unlike conventional fuels, its exothermic combustion process does not generate gaseous emissions, thereby distinguishing it as a potentially cleaner energy source. Owing to these properties, research on boron as an alternative fuel has been conducted since the 1950s. In addition to its application as a fuel, boron has also been considered a potential additive in engine fuels and lubricating oils, primarily due to its high combustion capacity and strong lubricating characteristics. The energy technologies of boron are thoroughly examined in this chapter.

Keywords – Boron, Combustion, Energy technology, Hydrolysis, Nuclear power

INTRODUCTION

The majority of the world's energy needs are now met by fossil fuels like coal, natural gas, an:d petroleum, but these resources are rapidly running out (Holechek vd., 2022:6). Additionally, the greenhouse effect, ozone layer depletion, acid rain, pollution, and other global issues brought on by their combustion products pose a serious threat to our environment and ultimately to life on Earth (Mathew vd., 2024:2; Karimi vd., 2025:8). To maximum decrease the excessive dependency on traditional fuels, the development of renewable and sustainable energy sources is of vital importance (Jaiswal vd., 2022:1). The creation of innovative materials instead of typical industrial goods is crucially necessary to handle the issue of deteriorative emissions as well as using renewable and clean energy (Altintas vd., 2016:8). Past decades have witnessed the rise of non–metal nanoparticles and nanocomposites for efficient energy generation, conversion and storage (Sohail, 2025:12). In both the past and present, the element boron has been crucial to many branches of science and technology. Boron is a significant element in the chemical world first discovered by Sir Humphry Davy, Joseph Louis Gay–Lussac and Louis Jacques Thénard in 1808 and it was first synthesized in pure form by Ezekiel Weintraub in 1909 (Halvaci vd., 2024:89). Because of its strength and capacity to hold its shape, boron has long been utilized in the production of glass and ceramics. It may also be utilized in a variety of applications, such as agricultural chemicals and textile dyeing, due to its antibacterial and preservation properties. Boron is a crucial element for activities such as plant development, photosynthesis and cell wall construction. Furthermore, one of boron's exceptional qualities is its application in the biomedical industry. In the aerospace and defense sectors, weight–broken boron–based materials with qualities like high hardness and low density can be used as a lighter and more durable substitute for steel (Ucuk ve Ucuncu, 2024:2). Thanks to improvements in energy technology and material sciences, boron is continually increasing relevance nowadays. Various boron compounds are applied in new applications such as the nuclear fusion, hydrogen generation and storage, lithium ion batteries, solar panels and combustion systems. Furthermore, boron–derived nanoparticles are equally suitable in green technologies, including the elimination of environmental contaminants and sustainable energy solutions. Boron is playing an increasingly significant role in the energy area (Kozhakhmetov vd. 2025:8). In conclusion, although boron has historically been utilized in traditional sectors such as glass, ceramics and textiles, in the present period it continues to play a significant role in various disciplines such as high–tech applications, the energy sector, biomedical breakthroughs and nanotechnology. The energy production technologies from boron are particularly investigated in this chapter.

CHARACTERISTICS OF BORON ELEMENT

Boron (atomic number 5, symbol B as in Figure 1) is a fundamental element of the boron group. In its crystalline state, it manifests as a brittle, glossy, black metalloid, whereas in its amorphous state, it appears as a brown powder (Abou Seeda vd., 2021). As the smallest member of the boron group, characterized by three valence electrons enabling covalent bonding, boron plays a crucial role in the synthesis of diverse compounds. These include boric acid, sodium borate minerals, and ultra–hard crystalline materials such as boron carbide and boron nitride (Tursucular, 2024).

With a high melting point of 2076°C and a boiling point of 3927°C, boron exhibits thermal stability that makes it an essential component of bodies intended for high temperatures (Cahill vd., 1989). Because of its high hardness and low density, the element is frequently used in lightweight, long–lasting materials. In the periodic table, boron is a binary element that lies between metals and non–metals. Its rich, multifaceted chemical structure enables it to interact with both metals and non–metals. These characteristics make boron useful in a wide range of scientific and industrial domains, and it is increasingly being employed in cutting–edge technological applications like nanotechnology (Halvaci vd., 2024).

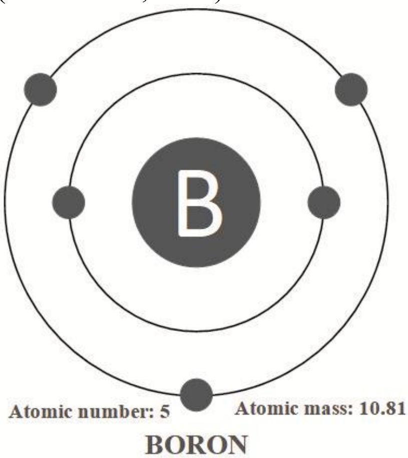

Figure 1. The chemical structure of boron

Boron is a relatively rare element in both the Solar System and the Earth's crust, as its origin is attributed exclusively to cosmic ray spallation and supernova explosions rather than stellar nucleosynthesis. It constitutes approximately 0.001% of the Earth's crust by weight. Due to the solubility of its naturally occurring minerals, known as borates, in water, boron tends to accumulate in specific terrestrial environments (Shearer ve Simon, 2017). Industrial extraction of borates, including kernite and borax, is generally carried out from evaporite deposits. The largest boron reserves are located in Turkey, the United States, Argentina, Russia, and China. Among these, Turkey possesses the most extensive reserves and is the leading producer of boron minerals. It is estimated that nearly 72% of global boron deposits, including colmanite and tincal, are concentrated in Turkey (Helvacı, 2017).

USAGE AREAS OF BORON

The primary utilization of boron is in the synthesis of chemical compounds. Approximately half of the global boron production is consumed in the manufacture of fiberglass, which is widely employed for insulation and structural applications. Another significant use is in the development of high–strength, lightweight, and heat–resistant materials, particularly ceramics and polymers (Iwan vd., 2023). Borosilicate glass, owing to its superior mechanical strength and resistance to thermal shock compared to conventional soda–lime glass, is therefore preferred in various applications. In the form of sodium perborate, boron functions as a bleaching agent. Smaller amounts are used as reagent intermediates in the synthesis of organic fine chemicals and as dopants in semiconductor production. Certain boron–containing organic pharmaceuticals are also utilized (Lima ve Monteiro, 2001). Nearly all boron extracted from the Earth is processed into sodium tetraborate pentahydrate and boric acid. In the United States, approximately 70% of boron consumption is directed toward the production of glass and ceramics. On a global scale, the manufacture of fiberglass for insulation and structural purposes–particularly in Asia–accounts for about 46% of industrial boron utilization. Boron is incorporated into glass as borax pentahydrate or boron oxide to enhance strength and fluxing properties. An additional 10% of global boron output is allocated to borosilicate glass for high–strength glassware. Super–hard materials and other boron–based ceramics consume around 15% of global production, while agriculture accounts for 11%, and bleaches and detergents for 6% (Elevli vd., 2022).

Boronated fiberglass: Boronated fiberglass is produced by incorporating borosilicate, borax, or boron oxide into fiber–reinforced polymers to enhance the mechanical properties of the glass. E–glass, an alumino–borosilicate glass with a high boron content, is widely employed in electrical applications. Similarly, C–glass, characterized by its elevated boron oxide concentration, is utilized in the production of glass staple fibers and insulation materials. D–glass, another borosilicate glass, is distinguished by its low dielectric constant, making it suitable for specialized applications. Due to the extensive use of fiberglass in construction and insulation, boron–containing fiberglass accounts for more than half of global boron consumption and represents the largest single commercial market for boron (Kudryavtsev vd., 2001).

Borosilicate glass: Borosilicate glass, typically composed of 12–15% B_2O_3, approximately 80% SiO_2, and 2% Al_2O_3, is distinguished by its low coefficient of thermal expansion, which provides exceptional resistance to thermal shock. Notable commercial examples include Duran (Schott AG) and Pyrex (Owens–Corning), both of which are extensively utilized in laboratory glassware as well as in consumer cookware and bakeware, primarily due to their enhanced durability and thermal stability (Hubert ve Faber, 2014).

Boron fiber: Boron fibers (filaments) are high–strength, lightweight materials predominantly employed in advanced aerospace engineering as components of composite structures. In addition, they are utilized in limited consumer and sports applications, such as golf clubs and fishing rods. These fibers are typically synthesized through chemical vapor deposition of boron onto tungsten filaments. When assisted by laser technology, chemical vapor deposition enables the fabrication of boron fibers and crystalline boron springs with sub–millimeter dimensions. Moreover, complex helical structures can be produced by translating the focused laser beam. Due to their favorable mechanical properties, such boron–based structures are suitable for use as ceramic reinforcements and in micromechanical systems (Görgün vd., 2021).

Boron carbide ceramic: Boron carbide is regarded as a highly effective material for neutron absorption in nuclear power plants, as it captures neutrons without generating long–lived radionuclides, particularly when enriched with the isotope boron–10 (^{10}B). Its applications in the nuclear industry include control rods, shut–down pellets, and radiation shielding. Within control rods, boron carbide is commonly employed in powdered form to increase surface area and thereby enhance neutron absorption efficiency (Uzun, 2023).

Boron in high–hardness and abrasive compounds: Boron carbide and cubic boron nitride (cBN) powders are widely utilized as industrial abrasives. Boron nitride, an isoelectronic analogue of carbon, exists in two principal allotropes: the cubic form (cBN), which is hard and diamond–like, and the hexagonal form (hBN), which is soft and graphite–like. Hexagonal boron nitride is commonly employed as a lubricant and as a structural component in high–temperature applications. In contrast, cubic boron nitride, commercially known as Borazon, is considered a superior abrasive due to its hardness–slightly lower than that of diamond–combined with greater chemical stability. Another boron–based compound, boron carbonitride (BCN), also referred to as hetero–diamond, exhibits properties closely resembling those of diamond (Çetin vd., 2015).

Boron in metallurgy: Small concentrations of boron, typically a few parts per million, are added to steels to enhance their hardenability. In the nuclear industry, higher boron contents are incorporated into steels due to the element's capacity to absorb neutrons. Through boriding, boron can also increase the surface hardness of steels and alloys. Furthermore, metal borides are employed as protective coatings for tools via chemical vapor deposition (CVD) or physical vapor deposition (PVD). The implantation of boron ions into metals and alloys by ion implantation or ion beam deposition significantly improves surface resistance and microhardness. Comparable results have also been achieved through laser alloying. These boride coatings serve as alternatives to diamond–coated tools, with the properties of treated surfaces being similar to those of bulk borides (Bekmezci vd., 2025).

Boron in detergent formulations and bleaching agents: Many home cleaning and laundry products contain borax. Additionally, certain tooth–whitening solutions contain it. Sodium perborate acts as a source of active oxygen in numerous detergents, laundry detergents, cleaning solutions, and laundry bleaches (Kulkarni vd., 2024).

Boron in insecticides and antifungals: Boric acid and zinc borates are commonly employed as pesticides and wood preservatives after becoming well–known as fire retardants. Boric acid is also utilized as a home pesticide (Schubert, 2019).

Boron in pharmaceutical and biological applications: Boron exhibits significant relevance in both biological and pharmacological contexts, as it is incorporated into several antibiotics produced by bacteria, including boromycins, aplasmomycins, borophycins, and tartrolons. Certain boron–containing biomolecules have the potential to act as signaling agents that interact with cell surfaces, thereby contributing to cellular communication. Due to its antibacterial, antifungal, and antiviral properties, boric acid is employed as a water clarifier in swimming pools and, in mild solutions, as an ocular antiseptic. In pharmacology, the organic compound bortezomib, a proteasome inhibitor used in the treatment of multiple myeloma and specific lymphomas, contains boron as an active component. Moreover, several boron–10 enriched compounds have been developed for boron neutron capture therapy (BNCT). For instance, dual–modality small molecules targeting prostate-specific membrane antigen (PSMA) have been tested in humans, enabling the localization of primary and metastatic prostate cancer, fluorescence–guided tumor resection, and detection of single cancer cells at tissue margins. Current research also investigates the incorporation of boron into biologically active compounds for therapeutic purposes, including BNCT for brain tumors. Enriched boron, particularly the isotope ^{10}B, remains the principal nuclide employed in cancer neutron capture therapy and radiation shielding. In BNCT, a ^{10}B–containing compound is administered and selectively absorbed by malignant tumors and surrounding tissues, thereby facilitating targeted therapeutic effects (Konaklieva ve Plotkin, 2024).

Boron in semiconductors: For semiconductors like silicon, silicon carbide, and germanium, boron is a helpful dopant. It contributes a hole and produces p–type conductivity because it has one fewer valence electron than the host atom. Boron is traditionally introduced into semiconductors through high–temperature atomic diffusion. Solid (B_2O_3), liquid (BBr_3), or gaseous (B_2H_6 or BF_3) boron sources are used in this method (Noffsinger vd., 2009).

Boron in magnets: Neodymium magnets ($Nd_2Fe_{14}B$), one of the strongest kinds of permanent magnets, contain boron. These magnets are used in much electromechanical and electronic equipment, including tiny and relatively small motors and actuators, as well as medical imaging systems that use magnetic resonance imaging (MRI). Neodymium magnet motors, for instance, provide powerful rotating power in a relatively small package for computer HDDs (hard disk drives), CDs (compact disks), and DVD players. Neo–magnets in cell phones create the magnetic field necessary for small speakers to produce noticeable audio power (Pourarian, 2000).

Boron in nuclear reactors: Boron is extensively utilized in nuclear reactor control systems owing to its high neutron capture cross–section. In pressurized water reactors (PWRs), variations in fuel reactivity are regulated by adjusting the concentration of boric acid in the coolant, where it functions as a neutron poison. The concentration of boric acid is initially highest when new fuel rods are introduced and gradually decreases over time. The isotope boron–10 (^{10}B) is particularly effective in capturing thermal neutrons; therefore, natural boron is enriched to nearly pure ^{10}B for nuclear applications, while the byproduct depleted boron, composed predominantly of boron–11 (^{11}B), has limited industrial value. Boron–10 is also employed in emergency shutdown systems and reactivity control, either in the form of boric acid or borosilicate control rods. In PWRs, ^{10}B–enriched boric acid is added to the coolant during reactor shutdown for refueling, and its concentration is gradually reduced over several months as fissile material is consumed and the fuel becomes less reactive upon reactor restart (Mesquita, vd., 2022).

ENERGY TECHNOLOGIES OF BORON

The energy generating methods of boron have been the focus of ongoing research. Fusion, hydrolysis, and combustion are the three primary categories of boron energy generation techniques, as shown in Figure 2.

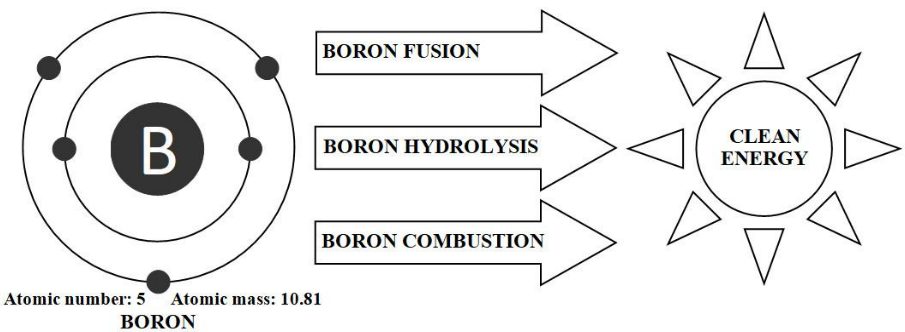

Figure 2. Energy production methods from boron

Boron fusion: The future of global energy production is expected to rely on a combination of nuclear power and renewable energy sources in order to mitigate the effects of global warming. Although nuclear fission is regarded as a reliable energy source, it poses potential risks to both human health and the environment. The management and disposal of radioactive waste generated by fission power require complex and highly regulated procedures to address radiation hazards. In contrast, nuclear fusion represents a clean and virtually inexhaustible energy source, offering significant promise for long–term energy sustainability, though its practical implementation remains a challenge that may only be realized over an extended period (El–Azeem, 2025).

Naturally occurring boron consists of two stable isotopes: boron–11 (^{11}B, 80.1%) and boron–10 (^{10}B, 19.9%), both of which possess nuclear spin. Due to its large neutron capture cross–section, ^{10}B is widely employed as a neutron–absorbing material for controlling fission processes in nuclear reactors. Although several industrial–scale enrichment techniques have been developed, only fractionated vacuum distillation of the dimethyl ether adduct of boron trifluoride (DME–BF_3) and column chromatography of borates are currently utilized (Sağlam ve Özdural, 2016).

The potential applications of boron have been extensively investigated within the field of nuclear fusion research. To condition reactor walls and minimize the release of hydrogen and other impurities, boron coatings are frequently applied to plasma–facing components in fusion systems. These coatings also contribute to the dispersion of energy within the plasma boundary, thereby mitigating excessive energy bursts and heat fluxes directed toward the walls. The isotope boron–11 (^{11}B) has been identified as a promising candidate for aneutronic fusion fuel, as proton bombardment at approximately 500 keV yields three alpha particles and 8.7 MeV of energy. Unlike conventional hydrogen–helium fusion reactions, which generate penetrating neutron radiation that damages reactor structures and induces long–term radioactivity, proton–boron fusion produces minimal neutron output. Consequently, the alpha particles generated from ^{11}B fusion can be directly converted into usable energy once the reactor is shut down. Naturally occurring boron consists of two stable isotopes, boron-10 (^{10}B) and boron–11 (^{11}B), with the latter comprising about 80% of the total. Owing to its high neutron capture cross–section, ^{10}B is widely employed as a neutron absorber in the nuclear industry and has also been utilized in boron neutron capture therapy (BNCT), a non–invasive cancer treatment method. Conversely, ^{11}B has attracted considerable interest following the discovery of proton–boron fusion (p–^{11}B), an aneutronic process in which protons and ^{11}B nuclei undergo fusion to produce energetic alpha particles with minimal neutron radiation. As illustrated in Equation 1, the fusion of a boron nucleus with a proton yields helium nuclei, which are considered a potential fuel source for controlled thermonuclear fusion reactors (Begrambekov ve Buzhinskij, 2007).

$$p + 11B \rightarrow 3\alpha + 8.7 \text{ MeV} \tag{1}$$

Over the years, researchers and theorists have focused on the p–11B reaction to extract energy from boron through aneutronic fusion. This fusion process should be possible without thermal equilibrium, according to Hora's prediction from the 1970s. However, extremely high temperatures and pressures are needed for hydrogen–boron fusion processes. This may be the reason why deuterium–tritium fusion has received more attention in research and development than proton–boron clean fusion (Chirkov ve Kazakov, 2023).

At the beginning of the twenty–first century, efforts to advance nuclear fusion as a viable energy source intensified. The ‘Z–machine’ at Sandia National Laboratories has been employed to establish conditions conducive to hydrogen–boron reactions. In this system, the plasma exhibits a unique reversed non–equilibrium state in which the ion temperature is approximately 100 times greater than the electron temperature. The approach, referred to as inertial confinement fusion, is distinctive in that it compresses the fuel using magnetic fields rather than lasers. In the coming years, Sandia researchers aim to further develop the supporting infrastructure for this concept. Concurrently, several commercial enterprises have invested in the development of safe nuclear reactions capable of directly generating electrical power. For example, the Jet Propulsion Laboratory and the Air Force Research Laboratory of NASA have provided funding to Lawrenceville Plasma Physics for theoretical and experimental studies on aneutronic proton–boron (p–^{11}B) fusion. Tri Alpha Energy (TAE) Technologies Incorporated, founded in 1998 to pursue aneutronic fusion power, is currently developing a device designed to fuse hydrogen and boron by colliding two plasmoid structures. Following significant private sector investment, TAE has announced plans to commercialize its fusion reactor technology within the next five years. HB11 Energy Proprietary Limited, an Australian company, has proposed an alternative strategy termed ‘Laser Boron Fusion,’ which seeks to generate power without the use of radioactive fuels or extremely high temperatures. Their reactor design employs two lasers positioned on either side of a central fuel pellet, producing alpha particles that can be directly harnessed by the electrical grid without the need for intermediate heat exchangers or steam turbine generators. Hydrogen–boron fusion, therefore, offers the potential to generate electricity instantaneously while avoiding the production of radioactive waste. HB11 Energy has secured patents for this laser–driven fusion process in 2020 and aims to deliver large–scale electricity for urban centers, as well as small–scale power for ships, mines, and industrial facilities, by 2050 (Elorriaga vd., 2021).

Boron hydrolysis: Among inorganic substances that can be utilized to chemically split water, boron has the highest gravimetric hydrogen production potential. Water and boron react to produce up to 3.0 liter of H_2 and 25 kJ/gr of heat. As seen in Equations 2 and 3, boron oxide gasification and boron oxide oxidation occur concurrently during the hydrolysis reaction (Lo vd., 2007).

$$2B_{(s)} + 3H_2O_{(g)} \rightarrow 3H_{2(g)} + B_2O_{3(l)} \quad \Delta H_{750K} = 506.6 \text{ kJ/mol} \quad (2)$$

$$B_2O_{3(l)} + 3H_2O_{(g)} \rightarrow 2H_3BO_{3(g)} \quad \Delta H_{750K} = -22 \text{ kJ/mol} \quad (3)$$

The interaction of boron with steam leads to the formation of gaseous boric acid through the reaction of the oxide layer with steam. Hydrolytic oxidation of boron occurs at lower ignition temperatures compared to oxidation in pure oxygen. This hydrolysis process generates volatile boric acid species, including metaboric acid (HBO_2), by removing the fluid oxide layer, which in turn creates technical challenges. Compared to combustion data, experimental data on boron hydrolysis remain limited. Research initiated in the 1990s demonstrated in 1998 that the combustion of boron in a heated steam environment could yield hydrogen. When amorphous boron powder samples reached approximately 450°C, corresponding to the melting point of boron oxide, superheated steam produced in an autoclave at an overpressure of 0.5 bar was injected into a reactor, resulting in a hydrogen yield of about 60% of the theoretical value. This process is considered hydrolysis of boron in the absence of oxygen at moderate reactor temperatures below 600°C, with confirmation that the reaction occurs only above the melting point of boron oxide. The hydrogen yield, ranging from 47% to 75% of the theoretical maximum, is determined by both temperature and the steam–to–boron ratio. Furthermore, studies have shown that in the presence of catalytic amounts of alkali metals or alkali metal hydrides, high–purity amorphous boron nanoparticles (BNPs) can undergo hydrolysis at ambient temperature without external energy input. BNPs produced via laser pyrolysis of diborane exhibit rapid water–splitting activity, generating hydrogen gas at room temperature when activated by alkali metals or NaH, in contrast to commercially available boron. In gas–surface reactions, boron nanoparticles and nanopowders provide ultra–high surface areas and enhanced reactivity. Thermodynamic analyses indicate that boron possesses significant potential for on–demand hydrogen generation through reactions with water. Mixtures of BNP and NaH appear promising for onboard hydrogen storage in light–duty fuel cell vehicles. Elemental boron reacting with water releases hydrogen, which can be utilized to power either fuel cells or internal combustion engines. For engine operation, steam must reach several hundred degrees Celsius. The water produced during hydrogen combustion is reheated by the exothermic oxidation reaction once the engine is initiated, creating a cyclic feed. Although this technique currently faces economic challenges compared to conventional fuels, it remains safe, relies on non–toxic materials, and represents a potential pathway for future water–fueled engines (Dokumacı vd., 2018).

Research on boron chemistry has primarily focused on its chemical hydrides, although a limited number of boron–containing systems exhibit hydrogen adsorption and desorption behavior similar to that of metal hydrides. Among these, sodium borohydride ($NaBH_4$) and its aqueous solutions represent the most advanced developments. Millennium Cell has commercialized sodium borohydride as a hydrogen source, utilizing a controlled, exothermic reaction between $NaBH_4$ and H_2O at ambient temperature. This process operates without the need for high pressure, avoids undesirable side reactions, and does not generate hazardous byproducts, as illustrated in Equation 4 (Dragan, 2022).

$$NaBH_{4(aq)} + 2H_2O_{(g)} \xrightarrow{\text{Catalyst}} 4H_2 + NaBO_{2(aq)} + Heat \tag{4}$$

As depicted in Figure 3, the hydrogen generation system stores sodium borohydride fuel solution in a tank and employs a compact reactor to produce hydrogen on demand. Hydrogen generation in sodium borohydride ($NaBH_4$) systems is controlled by regulating the contact between the fuel solution and the catalyst within the reactor. Following the reaction, the liquid metaborate byproduct is separated from the hydrogen gas. The heat released during the process converts a portion of liquid water into vapor, fully humidifying the hydrogen stream. This mixed hydrogen–water vapor stream can be directed to a heat exchanger to adjust the moisture content to the desired level prior to transfer to the fuel cell power module. The byproduct is subsequently removed from the system and either disposed of or recycled in a designated discharge area. The injection rate of the borohydride solution directly influences the volume of hydrogen produced during operation, with fuel supplied to the reactor only when hydrogen demand arises, allowing for straightforward control (Yolcular ve Karaoglu, 2020).

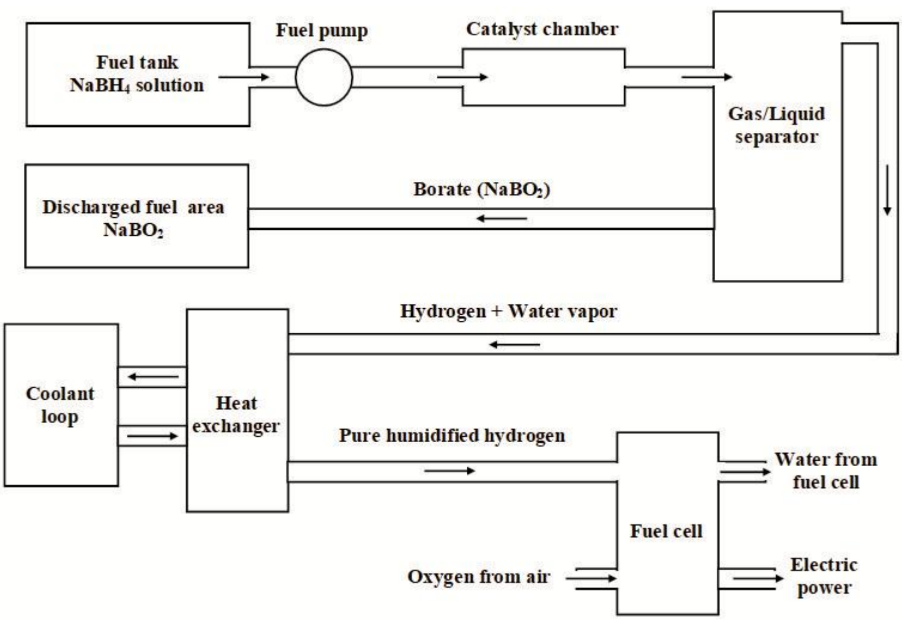

Figure 3. Hydrogen production via boron

The hydrogen generation rate from $NaBH_4$ solution is strongly correlated with catalyst concentration. Although the reaction can occur without a catalyst at a solution pH of nine, $NaBH_4$ is typically maintained in a strongly alkaline medium by the addition of NaOH to extend shelf life and prevent gradual hydrogen release during storage. In practice, hydrogen formation occurs only upon contact with the selected catalyst, as strongly alkaline $NaBH_4$ solutions do not produce significant hydrogen in its absence. Hydrogen production systems based on $NaBH_4$ offer several advantages, including the supply of pure, humidified hydrogen; high energy storage density; safe storage in plastic containers at ambient temperature without pressurization; environmentally benign, non–flammable, and non–explosive fuels and byproducts; adjustable hydrogen output flow rates and dispensing pressures; low operational complexity; and relatively simple production mechanisms. Despite these benefits, notable drawbacks remain. The process is costly due to the use of ruthenium, a rare and expensive catalyst, and the high price of $NaBH_4$ itself. For $NaBH_4$ to become a commercially viable hydrogen carrier, production costs must be significantly reduced. Current estimates suggest that, in fuel cell–powered vehicles, $NaBH_4$ alone would be approximately forty times more expensive than gasoline for covering the same distance (Kaya ve Bekirogullari, 2019).

Boron as fuel for fuel cell: The principal application of borohydride technology developed by Merit Limited is the direct borohydride fuel cell (DBFC). Unlike conventional fuel cells, DBFCs utilize borohydride dissolved in aqueous solution as the fuel source. This approach offers several advantages over the use of gaseous hydrogen. Most notably, storage–related challenges are eliminated, as DBFCs do not require specialized equipment such as hazardous high–pressure cylinders or energy–intensive liquefaction systems. Borohydride fuel is considered as safe as gasoline, operates at low temperatures, and possesses a high hydrogen capacity. Furthermore, DBFCs are more cost–effective and exhibit superior performance compared to other fuel cell technologies. Their enhanced efficiency arises from the release of eight electrons during the electrochemical process, rather than solely generating hydrogen for subsequent power conversion. By directly decomposing and oxidizing the fuel, DBFCs achieve higher energy yields. In addition, DBFCs do not rely on expensive platinum catalysts and provide greater power output per unit mass than conventional fuel cells, thereby offering the potential for more affordable large–scale deployment (Ma, 2016).

A side reaction between sodium borohydride ($NaBH_4$) and fuel cell–heated water results in the generation of hydrogen within direct borohydride fuel cells (DBFCs). This hydrogen can either be directed to a conventional hydrogen fuel cell or released through the exhaust. Higher concentrations of $NaBH_4$ may be achieved by recycling the water produced by the fuel cell in either case. Upon releasing hydrogen and undergoing oxidation, $NaBH_4$

forms sodium metaborate ($NaBO_2$). Although $NaBO_2$ is toxic to ants and is used as a component in ant poisons, it is generally considered inert and non–toxic, with applications as an additive in soaps and detergents. In DBFC systems, $NaBO_2$ waste can be collected in a designated waste tank or bladder within the fuel tank. Several methods have been proposed for re–hydrogenating $NaBO_2$ back into borohydride fuel, some requiring only heat, energy, and water. These regeneration techniques are under continuous development to enhance the sustainability of borohydride–based fuel systems (Özkar ve Zahmakıran, 2005)

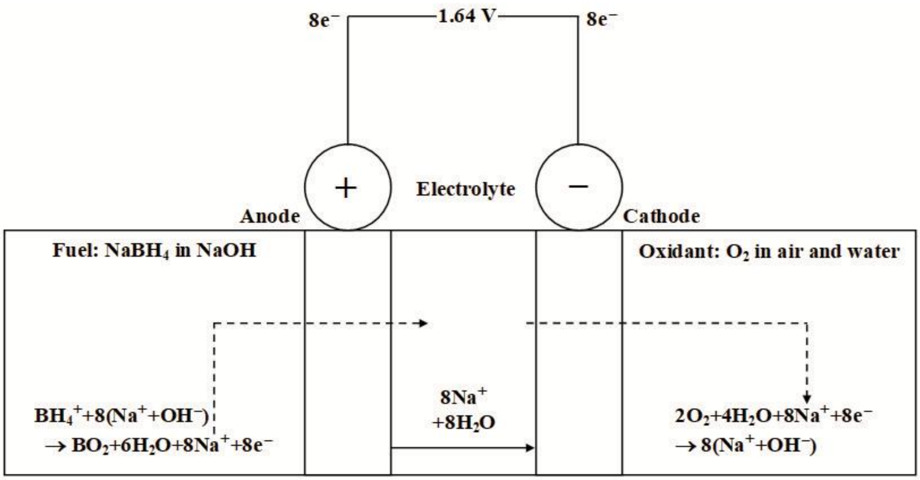

Figure 4. Electrode reactions in DBFC

Boron combustion: Although boron possesses a high molar heat of combustion (636 kJ/mol), initiating its combustion is challenging. Elemental boron does not react with air at ambient temperature. At elevated temperatures, boron undergoes combustion to form boron oxide (B_2O_3), as represented in Equation 4, with the released energy being influenced by factors such as crystallinity, temperature, particle size, and purity. In its liquid state, boron oxide functions as an effective solvent and may be employed as a flux to dissolve metals. However, this property can also lead to the degradation of engine components exposed to it, unless they are composed of resistant or specialized materials (Han vd., 2023).

$$4B_{(s)} + 3O_{2(g)} \rightarrow 2B_2O_{3(l)} \qquad (5)$$

Boron oxide is produced by the exothermic combustion process, which also produces no hazardous pollutants, byproducts, or other emissions. Compared to traditional liquid and gaseous fuels, the oxide is safer, easier to transport and takes up less room. Reversing the reaction is possible, but it would take a lot of energy to break down boron oxide into its constituent parts. Reduction with magnesium or aluminum does not yield pure boron and has the additional expense of producing reductants. Significant operational and safety costs are associated with elemental boron from the halide. In the future, the oxide might be broken back into boron using nuclear energy in automotive engines. (Gökdai vd., 2017).

Despite its advantageous properties, elemental boron also exhibits several limitations that hinder its effectiveness as an energy source. Owing to the presence of a natural boron oxide (B_2O_3) layer of approximately 0.5 nm, boron is difficult to ignite. Its activation energy is about 300 kJ/mol, significantly higher than that of hydrocarbons such as octane, which exhibit activation energies near 40 kJ/mol. During combustion initiation, most of the supplied energy is consumed in heating the boron particles. At elevated temperatures, the oxide layer melts, and the liquid oxide gradually becomes enriched with boron as dissolved boron diffuses through it in the form of $(BO)_n$ polymers. Consequently, the complete utilization of boron's combustion energy remains challenging. Since the 1960s, both theoretical and experimental studies have investigated boron oxidation, leading to the development of several strategies to improve particle ignition. These include ignition in halogen–containing environments, application of thin metal coatings, removal of the oxide layer with lithium fluoride (LiF) coatings, cleaning with acetonitrile to eliminate hydrated surface oxides, and doping with less than 5% transition metals (e.g., Fe or Hf) via wet synthesis or high–energy ball milling. Another approach involves the use of nanoparticulate boron, which, due to its high specific surface area and reactive surface atoms, demonstrates favorable combustion characteristics. Nanostructured particles can achieve complete combustion with high enthalpies and low–emission products. However, comprehensive studies on the ignition and combustion behavior of boron nanoparticles (BNPs) remain limited. Although the oxide layer is thinner on nanoparticles, the reduced elemental boron content compared to larger particles results in negligible effects on ignition. Similarly, particle size has been shown to be non–critical during combustion, as temperature variations dominate the process. Particles smaller than 1 μm fail to generate sufficient heat below 1770°C, whereas particles larger than 2 μm can transition into the liquid phase at temperatures near 1770°C. Studies on BNP combustion in ethanol spray flames revealed that ignition delay increases with particle size, while smaller particles achieve complete conversion. Since the early 2000s, nanoscale energetic particles have been introduced to enhance fuel and propellant performance. A promising emerging application is the incorporation of energetic BNPs as additives in liquid fuel combustion systems, which significantly increases volumetric heat output compared to conventional propellants (Jiang vd., 2020).

Boron as engine fuel: Compared to other metals, petroleum, and hydrogen, boron combustion releases significantly more energy per unit volume. The energy yield from boron combustion is approximately five times greater than that of petroleum. Owing to this property, boron has been proposed as a potential motor fuel. Boron fuel consists of elemental boron, which is combined with pure oxygen within the engine. Although ignition is difficult due to boron's inherent stability, this characteristic enhances safety in automotive applications, as highly flammable fuels often increase accident risks. In addition, boron possesses a higher energy content than petroleum–derived fuels. Its high energy density allows for storage chambers and waste bins of comparable size to conventional liquid hydrocarbon tanks, making it practical for vehicular use. Vehicles powered by boron fuel would achieve true zero emissions, as combustion produces only boron oxide (B_2O_3), which condenses into a solid and can be collected at fueling stations for recycling back into elemental boron. Boron combustion requires pure oxygen, and the sole byproduct is solid boron oxide, with no hazardous pollutants or greenhouse gases generated. Due to its compactness and energy density, boron fuel has the potential to enable transcontinental ranges. The byproducts B_2O_3 must be recycled through decombustion and stored onboard until exchanged for fresh boron fuel. Under conditions of pure boron combustion with a four–thirds excess of oxygen at 100 bar pressure and an initial temperature of 25°C, a maximum flame temperature of 4370°C can be achieved (Young vd, 2013). The combustion reaction of boron is represented in Equation 6.

$$B_{(s)} + 0.75O_{2(g)} \rightarrow 0.5B_2O_{3(gls)} - 590.76 \text{ kJ/mol} \tag{6}$$

Through a tiny opening in the wall of the combustion chamber, boron is supplied to a combustor as filament at a controlled pace. The filament tip will come into contact with a constantly burning fire inside the chamber as shown in Figure 4, which will quickly consume it. Boron may be almost impossible to ignite in air. When pure oxygen and high pressure are available, boron burning occurs. This implies that air and oxygen need to be kept apart. A heated metallic silver filter can be used to separate pure oxygen from air (Xia vd., 2006).

Technological advancements in boron–based engine systems are essential for the widespread and commercial adoption of boron as an automotive fuel. A major challenge lies in the reliable acquisition of pure oxygen in the required quantities. Although purification can be achieved through silver filters, maintaining a continuous supply of pure oxygen at the necessary stoichiometric ratio for high–speed vehicles remains problematic. Moreover, test driving has not yet been conducted, and the technology has not been experimentally validated in an operational automobile. Once the system reaches full functionality, comprehensive cost analyses will be required to assess its economic feasibility (Karataş vd., 2023).

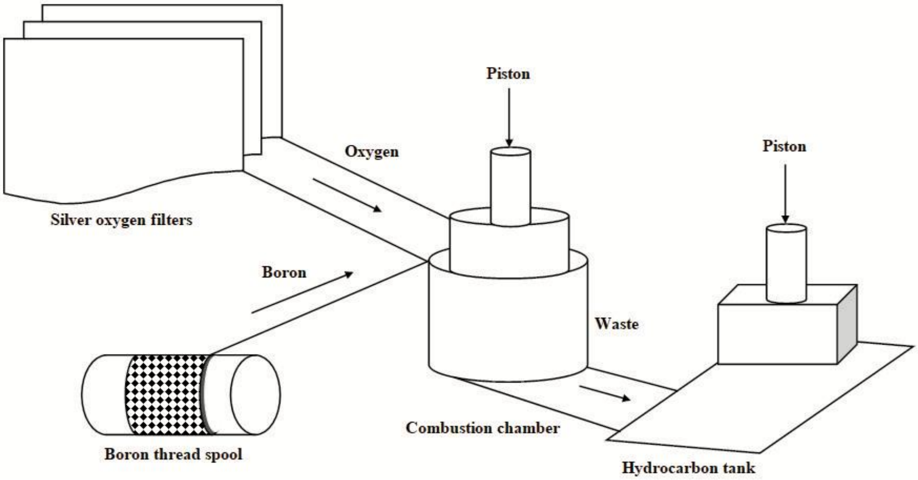

Figure 5. Layout of boron fuelled engine system

Boron as additive for engine fuels and oils: Metal fuels are considered promising candidates for battlefield power sources and unmanned military vehicles. A fuel in which a metal with a high heat of combustion constitutes the primary component is referred to as a metal–based fuel. In rocket propulsion or air–breathing engines, the high combustion enthalpy of such fuels translates into superior propellant performance. Among the available options, boron has emerged as one of the most favorable metals for fuel applications. Boron particles have been incorporated into solid propellants to increase combustion heat and mitigate specific types of combustion instability. Metallized components can be employed in both liquid and solid propellants, with emulsifying or gelling agents used to maintain uniform suspension when pure metals are added to liquid fuels. Since the 1950s, boron–based fuels have been investigated and applied in various military missile systems, including ramjet–powered designs. Furthermore, boron is regarded as a viable additive to conventional fuels, as its high energy density enhances combustion efficiency. Recent advances in nanotechnology have facilitated the incorporation of boron into fuels and oils, thereby improving performance and broadening its potential applications (Luigi vd., 2013).

Table 1 show the variation in performance and emissions by using boron including additives in fuels and also lubricants. As presented in Table 1, boron–containing additives enhanced combustion; however, their influence on performance parameters–including power, torque, efficiency, and fuel consumption–was less pronounced than their impact on emissions.

Table 1. Variation in performance and emissions by using boron including additives

Base fuel/oil and blending material	Variation (%)									Ref.
	Torque	Power	BSFC	BTE	CO	HC	NO_X	Smoke	CO_2	
Gasoline+TMB	–	–	–	–	3.4–12.1↓	4–14.4↓	6.7–57.2↑	–	15↑	(Gültekin, vd., 2023)
Gasoline+0.7% B including additive	1.1–5.2↑	–	2.1–9.5↓	–	7.4–29↑	28.7–46↓	–	–	–	(Sertkaya vd., 2016)
Gasoline+0.5% Octamix	–	–	–	↑	8.05↓	6.41↓	7.63↓	–	8.05↑	(Simsek, vd., 2022)
Gasoline+AB	4.4↓	–	0.4↑	–	1.7↑	6.7↓	–	–	5.1↓	(Dogu vd., 2020)
Gasoline+BA	4.4↓	–	15.2↓	–	0.9↑	2.7↓	–	–	5.2↓	
Gasoline+BP	4↓	–	5.8↓	–	3↑	0.2↓	–	–	2.5↓	
Gasoline+5%Ethanol+SBH	1–1.6↓	–	1–2.8↑	5.8–10.9↑	50–91↓	7.4–12.3↓	19.65↓	–	–	(Yakın vd., 2022)
Gasoline+5%Methanol+SBH	1.2–3.7↑	–	7.8–14.5↑	5.4–7.9↑	25–69↓	7.4–12.3↓	36.03↓	–	–	
Gasoline+10%Ethanol+SBH	↓	–	↑	↑	53.7↓	–	8.73↓		19.51↑	(Behcet vd., 2022)
Gasoline+10%Methanol+SBH	↑	–	↑	↑	–	–	–	–	–	
Gasoline+20%Ethanol+SBH	1.64↓	5.1↓	6.57↑	–	↓	↓	↑	–	↑	(Yakın vd., 2021)
Diesel+2.5% B	–	–	3.4↓	8.2↑	2.5–12↓	52↑	–	6↑	–	(Mehta vd., 2014)
Diesel+1% Octamix	–	–	7.8↓	3.19↑	46.67↓	13.79↓	15.66↓	10.714↓	23.63↓	(Simsek vd. 2021)
Diesel+20% BD+50, 100, 200 ppm BO	–	–	1.66↓	0.96↑	1.29↓	22.12↓	6.05↓	31.03↑	–	(Cakmak vd., 2022)
Diesel+50 and 100 ppm B	–	–	1.3–6.7↓	1.3–7.1↑	21–60↓	12.5–38↓	12.4–35↑	–	3.3–20.3↓	(Kül vd., 2022)
Diesel–CNG+50 and 100 ppm B	–	–	1.3–6.2↓	1.4–6.3↑	4–8.1↓	1.6–12.5↓	3.6–16↓	–	0.6–20.3↓	
Diesel–BG+100 ppm B	–	–	8.42↓	8.04↑	22.2↓	23.5↓	4.9↓	–	–	(Polat vd., 2022)
JP5+1, 2, 4% MNP	–	–	5↑	–	↑	↓	↑	–	↑	(Fisher vd., 2017)
Two stroke engine oil+hBN	–	–	12.5↓	–	↓	↓	–	–	↑	(Orman, 2023)
10W–40 oil+10% B in gasoline engine	0.4–1.3↓	–	3.4↓	–	NA	NA	12.3↓	–	NA	(Akbıyık vd. 2022)
10W–40 oil+10% B in CNG engine	1.3–2.1↑	–	7.1↓	–	NA	NA	11.4↓	–	NA	
10W–40 oil+15% B in diesel engine	2.5–8.3↓	–	12.3–14.6↓	–	29.43↓ 81.27↑	51.58–84.41↓	68.57–83.08↓	–	57.83–68.72↓	Karatas vd., 2023)
20W–40 oil+1% hBN in diesel engine	–	–	3.5↓	6.3↑	46.15↓	55.95↓	40.03↑	–	–	(Ramteke vd., 2020)
20W–50 oil+4% hBN in diesel engine	–	–	3.9–4↓	–	–	–	–	–	–	(Bas vd., 2014)

AB: Anhydrous borax, B: Boron, BA: Boric acid, BD: Biodiesel, BG: Biogas, BO: Boron oxide, BP: Borax pentahydrate, BSFC: Brake specific fuel consumption, BTE: Brake thermal efficiency, CNG: Compressed natural gas, CO: Carbon monoxide, CO_2: Carbon dioxide, hBN: Hexagonal boron nitrate, HC: Hydrocarbon, MNP: Metallic nanoparticle, NO_X: Nitrogen oxides, SBH: Sodium borohydride, TMB: Trimethyl borate

CONCLUSIONS

The energy technologies of boron are thoroughly examined in this chapter and following conclusions can be summarized.

- The rapid growth of the global population, coupled with the progressive depletion of fossil energy resources, has compelled scientists to explore alternative solutions to meet the increasing worldwide energy demand.
- Hydrogen–boron fusion is considered more promising as it offers a clean nuclear fuel with no waste. This fusion reaction can yield three to four times more energy per unit mass than nuclear fission, without associated risks. Ongoing research and technological progress in proton–boron fusion highlight its potential as a sustainable future energy source.
- Elemental boron is recognized as an efficient energy carrier and is increasingly regarded as one of the prospective energy sources of the future. Owing to its unique physicochemical properties, boron is considered a potential natural renewable resource capable of substituting conventional fuels.
- Boron can react with water to produce hydrogen quickly enough to power vehicles, offering hydrogen on demand. However, practical use of boron combustion and hydrolysis is still limited. Nanotechnology, especially reducing boron particles to the nanoscale, is expected to solve these challenges in the near future.
- Combustion in pure oxygen produces only solid boron oxide, which must be recycled, and ignition remains a major challenge. Developments in nanotechnology made possible the producing of boron–including fuel additives more efficiently.
- Intensified researches are needed to reduce costs and expand using of boron in energy systems.

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The Importance of Innovation in Mechanical Engeering Education

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ABSTRACT

Mechanical engineering stands out as a dynamic and innovative field today under the influence of rapidly advancing technology. In this context, the adoption of innovation in mechanical engineering education plays a critical role in ensuring that graduates gain competencies that meet the demands of modern industry. Innovation is not limited to technical knowledge; it is also important for students to develop their problem-solving abilities, creativity, entrepreneurial skills, and digital transformation capacities. This book examines the importance of innovation and how it can be integrated into mechanical engineering education. Topics such as adapting educational programs to today's needs, using project-based learning methods, establishing strong collaborations with industry, and integrating new technologies into education are discussed in detail. By incorporating contemporary engineering approaches such as digitalization, automation, artificial intelligence, and sustainability into the education process, it becomes possible for students to gain competencies that can compete on a global scale. Innovation-based approaches in mechanical engineering education train future engineers as more creative, flexible, and solution-oriented individuals, while also enabling the implementation of projects that add value to the industry. Prioritizing innovation in education not only aims to increase academic success, but also to establish strong ties with industry and contribute to social development.

Keywords: Innovation, Mechanical Engineering, Education, Sustainable

INTRODUCTION

Mechanical engineering stands out as a dynamic and versatile discipline that has been the basis of engineering solutions and technological progress since the industrial revolution. This field is not limited to the design, production and maintenance of mechanical systems and machines; it has an important role in innovative and critical areas from energy systems to automation, robotics to material science, artificial intelligence to sustainable engineering (Setiyo & Rochman, 2023).

It is known that the first official engineering school in the world was opened in France in 1757. Following this development, Ecole Polytechnique was established in France in 1794. In the United States, military engineering education became official and was first offered in an organized manner in 1817 at the West Point Military Academy. In the mid-19th century, Harvard, Yale and Dartmouth universities included engineering education in their academic programs, but Harvard University later removed this field from its curriculum. In addition, new technical institutes such as Rensselaer

Polytechnic Institute and MIT emerged and contributed to the development of engineering education. As of 1870, the number of institutions providing engineering education in the USA reached 70, and this number increased to 250 by 1990 (Adams, 1996).

Today, rapidly changing technology and economic dynamics often cause ongoing engineering approaches to be inadequate. In this context, the importance of innovation in the mechanical engineering education process has increased and it has become a necessity for students to not only acquire basic engineering knowledge but also to develop their creative thinking, problem solving and interdisciplinary work skills (Cropley, 2015).

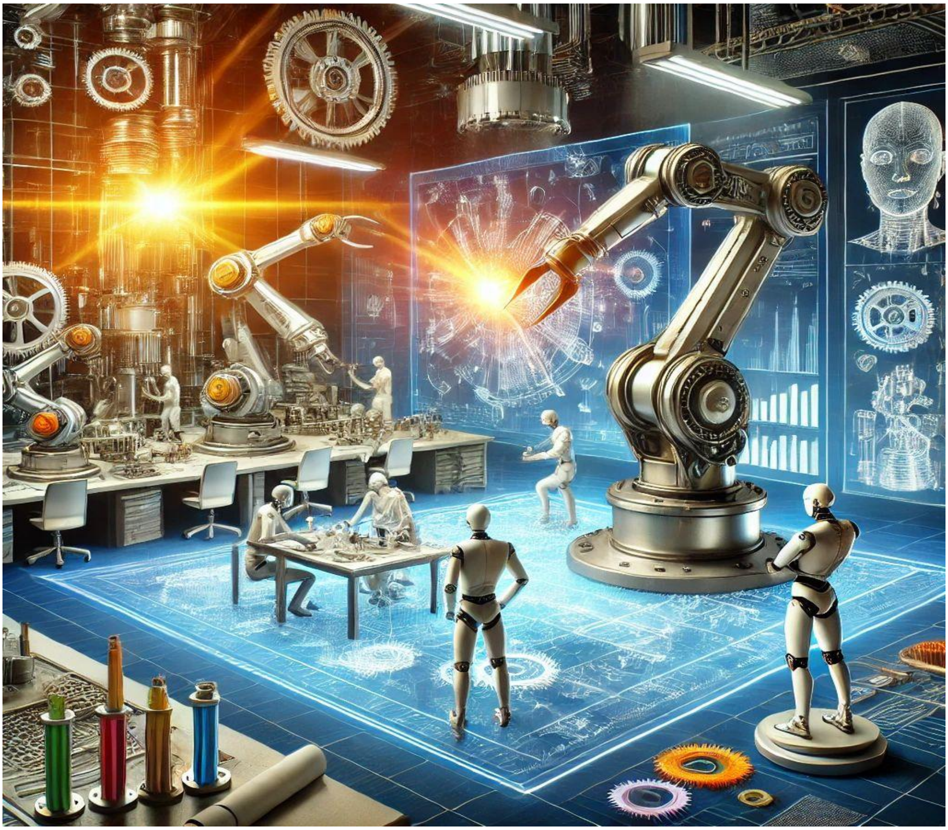

Figure 1. Innovation in Mechanical Engineering (AI-generated visual)

Innovation is generally defined as the process of producing new and more efficient engineering solutions (Kline & Rosenberg, 2010). However, in the context of education, this concept has a much broader meaning, and aims to provide students with the ability to develop effective solutions to future problems, rather than just being content with existing solutions. This approach goes beyond the theoretical knowledge transfer of engineering education and focuses on making students active problem-solving processes, critical evaluations, and the center of creative solution production.

Innovation, especially in the context of mechanical engineering, means the effective use of technology, transformation in teaching methods, keeping the curriculum up-to-date and integrating students into these processes with innovative methods. The reshaping of the engineering world with transformative technologies such as Industry 4.0, artificial intelligence, cyber-physical systems and advanced robotics has made it inevitable for mechanical engineering education to be comprehensively restructured (Lv et al., 2024). Innovative approaches have become a critical need to keep up with this rapid change. It is of great importance for both students and instructors to adopt modern technology tools, current engineering disciplines and innovative educational strategies in order to adapt to these developments.

Innovation in education is not limited to the inclusion of technological developments in course content, but is also related to the implementation of new pedagogical methods that place the student at the center of the learning process and encourage participation and collaboration. Such approaches aim to provide both technical knowledge and social skills such as leadership, communication and teamwork. These competencies, especially needed in contemporary engineering careers, can be effectively developed by creating learning environments that support innovation (Dewra, 2025). Modern mechanical engineering education requires not only the expanded use of technological tools but also the diversification of educational methods. The use of tools such as project-based learning models, virtual laboratory applications, 3D printers and cyber-physical systems have been effective in increasing both the creative and analytical capacities of students (Montesinos et al., 2022).

In addition, the experiences students gain through real-world projects and industrial collaborations enable them to put their theoretical knowledge into practice, allowing them to be better prepared for life. Such direct collaborations make engineering education more directly related to real-life needs and provide students with experiential learning opportunities (Juarez-Ramirez et al., 2016).

In summary, innovation encourages an understanding that includes not only the technical aspects of engineering education, but also broader issues such as social responsibility and sustainability. Given the increasing need for environmentally responsible engineering solutions in today's industry, mechanical engineering education should go beyond simply transferring technological knowledge. This education should adopt a more comprehensive approach by providing opportunities to implement innovative solutions in the context of environmental impacts and social responsibilities. Such a method allows engineering education to establish stronger ties with social life, while also contributing significantly to the development of students as socially responsible engineers.

This book demonstrates the role and value of innovation in education with the example of mechanical engineering, with relevant practical examples. Educational innovation is first addressed within the framework of a mechanical engineering discipline. This book explains innovation in education within the boundaries of mechanical engineering. On the other hand, the beneficial effects of digital technologies and synergy with industry will be discussed with examples from current innovative practices and new educational methods applied in this field. Innovation in education supports students to experience a multifaceted development process by providing them with effective technical knowledge and skills that enable them to develop creative thinking, effective problem solving and leadership competencies.

DEFINITION OF INNOVATION AND ITS IMPORTANCE IN MECHANICAL ENGINEERING EDUCATION

Innovation refers to the creation of a new invention or the significant development of an existing product, process or service. This concept, which is often limited to the creation of innovative ideas, actually includes the process of implementing, developing and creating economic value for these ideas. Innovation is not limited to technological change, but also has the power to effectively transform and change in social, cultural and economic areas, and in this respect, it plays a critical role. Directly linked to creativity and innovative thinking, innovation is usually based on original ideas that offer more effective, efficient or sustainable alternatives than existing solutions.

However, the innovation process is not limited to the design of new products or services; it also includes the development of new business models, production methods or organizational structures. From this perspective, innovation is not just a field focused on engineering or technology, but has become a strategic instrument that increases competitive advantage in many sectors, transforms economic structures and accelerates social progress (Zhu, 2024).

Types of innovation can be broadly divided into two main categories:

- **Product Innovation**: New products or redesign of existing products with significant improvements to address changing needs.

- **Process Innovation**: Developing new production methods, organizational processes or ways of doing business in order to adapt to the modern world.

Engineering disciplines such as mechanical engineering do not limit innovation to the development of new products. This concept enables significant developments in a wide range of fields, from process engineering to energy efficiency, from materials science to robotics and automation, from artificial intelligence applications to sustainable engineering. In engineering education, innovation aims not only to transfer existing theoretical and practical knowledge to students; but also to produce innovative and more effective engineering solutions by using this knowledge creatively (Hull & Motahari Nezhad, 2016).

The Importance of Innovation in Mechanical Engineering Education

In light of today's technological advances and changing needs in the industrial sector, mechanical engineering education should embrace innovation as one of the fundamental elements of the educational curriculum rather than seeing it as merely a supporting concept. This perspective aims to not only provide students with the knowledge and skills specific to the field of engineering, but also to train them to produce solutions to the engineering problems they will face in the future and the rapidly developing technological transformations.

The importance of innovation in mechanical engineering education can be deepened under the following main headings:

a. Ability to Respond to Industry Needs

The main goal of mechanical engineering education is to equip students with the knowledge and skills to respond to rapidly changing and increasingly complex industrial needs. Modern industrial revolutions such as Industry 4.0 have necessitated transformation in a wide range of areas, from manufacturing processes to technological applications. Advanced technologies such as cyber-physical systems, the Internet of Things, artificial intelligence, and robotics are among the critical elements that have radically changed traditional engineering approaches (Mullett, 2022). Therefore, it is of great importance to integrate these technologies into the mechanical engineering curriculum and provide students with comprehensive education in these areas. In addition, having in-depth knowledge in areas such as systems engineering, big data analytics, energy efficiency, and sustainable design plays a critical role in individuals' success in their careers. Such an innovative and versatile educational approach will provide students with the ability to effectively and creatively address future industrial challenges and turn them into individuals who will lead their sectors (Isaza Domínguez et al., 2024).

b. Developing Creative and Innovative Solutions

Mechanical engineering education should not be limited to the transfer of technical knowledge, but should also aim to increase students' creative thinking skills and their capacity to produce innovative solutions. Students should be encouraged to develop different perspectives beyond traditional approaches to engineering problems and to design original solutions accordingly. In this context, contemporary pedagogical methods such as Problem-Based Learning (PBL) and Design Thinking aim not only to teach engineering principles, but also to show how the acquired knowledge can be applied in creative and innovative ways. Such an educational approach both provides students with self-confidence and strengthens their analytical thinking skills, making them more innovative and effective individuals in the field of engineering (Widiastuti et al., 2023).

c. Multidisciplinary Approaches

Today, solving engineering problems often requires a multidisciplinary approach. Mechanical engineers do not only deal with mechanical systems; they also work with different fields such as electrical engineering, software development, biotechnology and materials science to produce innovative solutions. The combination of these disciplines forms the basis of creative engineering solutions. For example, fields such as bioengineering and nanotechnology offer new perspectives and opportunities by transcending the traditional boundaries of mechanical engineering. For this reason, it is of great importance that mechanical engineering education programs are designed in a modern and innovative structure and include multidisciplinary approaches. Learning methods supported by interdisciplinary projects and including teamwork allow students to combine and integrate information from different fields, while also increasing their ability to develop comprehensive engineering solutions (Muttaqin, 2025).

d. Sustainability and Social Responsibility

There is another important aspect of innovation in engineering education: promoting a sustainable engineering mindset and strengthening the sense of social responsibility. Today's engineering solutions must go beyond mere efficiency and performance; they must also be designed with environmental awareness and societal needs in mind. New ideas and applications can lead to significant advances in areas such as the use of environmentally friendly materials, renewable energy systems, low-carbon production methods and energy efficiency. In this context, mechanical engineering education should aim to increase students' awareness of the need to develop sustainable solutions and to provide them with the knowledge and tools necessary to achieve these goals. Given the societal impact of engineers, their ethical responsibilities and the environmental consequences of their work, these elements should be seamlessly integrated into innovation processes (Sánchez-Carracedo & López, 2020).

e. Technological Transformation and Digitalization

Mechanical engineering education is currently being reshaped by going beyond focusing solely on innovation and integrating digitalization and new technologies. Technological advances are changing the way students view engineering problems, allowing them to adopt a more flexible and dynamic approach than traditional methods. For example, 3D printers and rapid prototyping technologies accelerate design and production processes, allowing students to develop concrete prototypes in a short time. In addition, virtual reality (VR) and augmented reality (AR) applications make complex engineering concepts more understandable, while advanced technologies such as artificial intelligence and machine learning make significant contributions to data analysis and optimized solution development processes (Goyal et al., 2025). Integrating these digital tools into educational processes enables engineering students to work more efficiently and produce innovative solutions, effectively preparing them for the engineering world of the future. Innovation in mechanical engineering education includes not only the use of new technologies but also the holistic integration of these technologies into educational processes. This approach aims to provide students with multi-faceted competencies. Innovative engineering education should not be limited to the transfer of technical knowledge; it should also support the development of basic skills such as creativity, collaboration and social responsibility. Such an educational model will enable future engineers to reach the capacity to provide more effective, efficient and sustainable solutions for both industry and society.

INNOVATION APPLICATIONS IN MECHANICAL ENGINEERING EDUCATION

Mechanical engineering education is now moving away from traditional methods and adopting more innovative and dynamic pedagogical approaches. These approaches not only provide students with technical knowledge, but also enable the development of critical competencies such as creativity, problem-solving skills and interdisciplinary collaboration. An innovative education approach is not limited to the integration of technological tools and digital solutions into learning processes; it also aims to make these processes more interactive, student-centered and compatible with the current needs of the sector (Widiastuti et al., 2023).

In the following sections, contemporary methods used in mechanical engineering education, technological tools in education and implemented projects are examined in detail. In this context, examples are presented that combine theory and practice, enrich the learning experience of students and prepare them for the real needs of the engineering world.

Problem-Based Learning – (PBL)
Problem-Based Learning (PBL), as an effective and rational pedagogical model, aims to develop creative thinking and problem-solving skills by exposing students to real engineering problems. In this approach, unlike traditional education methods, the teacher does not present all the information from the beginning. Instead, students are introduced to realistic engineering problems and encouraged to research, discuss, and apply what they have learned. PBL is used in a wide variety of areas such as design projects, system optimization, and problem-solving scenarios in mechanical engineering education. A fundamental element of this method is the provision of interdisciplinary collaboration and teamwork to produce solutions to specific engineering problem sets (Pawar et al., 2020).

- **Machine design projects**: Students focus on designing a machine to solve a specific problem, using both technical knowledge and creativity in the process.
- **Simulation and modeling problems**: Students develop different solution approaches by modeling physical systems in a digital environment. Such applications enable them to learn analysis and optimization processes through engineering software.

Design Thinking
Design Thinking brings an innovative approach to the engineering design process, allowing students to develop creative solutions, brainstorm, create prototypes, and test these prototypes. With its user-centered structure, it can make engineering products more compatible with social needs and user expectations. In mechanical engineering education, design thinking not only supports the development of problem-solving and technical skills, but also aims to make students aware of social problems and suggest innovative decisions. Design-oriented studies help students adopt creative engineering methods that focus on key criteria such as sustainability, ergonomics, efficiency, and cost (Zhang et al., 2024).

In this context, the application areas of design thinking include:

- **Designing user-friendly machines**: Students design a machine with users' needs in mind, a process that includes ergonomics and user feedback.
- **Sustainable design projects**: Designs that minimize environmental impacts and provide energy efficiency are studied. Students gain in-depth knowledge of environmentally friendly materials and production processes.

Digital Tools and Simulations
Digital tools and simulation software allow mechanical engineering students to better understand and analyze complex engineering designs and systems.

Among the advanced technologies, Virtual Reality (VR), Augmented Reality (AR), and Finite Element Method (FEM) are prominent tools that provide great advantages to students when creating solutions to real-world engineering problems. Digital simulations enable extensive testing of designs before physical prototypes are made, saving time and money. These technologies not only add practical application skills to engineering education, but also increase the overall efficiency of processes (Abulrub et al., 2011).

Examples of digital tools and simulation applications include:

- **Machine design using CAD software:** Students model machine designs in a computer environment and test them with various simulations. These software programs allow them to evaluate the functionality and durability of the designs.
- **FEM analysis:** Students test the safety and efficiency of their designs by analyzing mechanical systems, including stress, strain, and temperature distribution.

Rapid Prototyping and 3D Printers

Rapid prototyping represents an efficient method for students to create physical designs, with the advent of 3D printers serving as a pivotal innovation in this domain. These technologies enable students to swiftly convert digitally conceived designs into tangible prototypes, facilitating practical testing and refinement. Their utility is particularly evident in machine-building education, where they bridge the gap between theoretical knowledge and practical application, providing a clearer understanding of concepts. Moreover, 3D printing has significantly accelerated the process of testing and developing innovative ideas, simplifying what was once a more time-consuming and complex endeavor (Lifton et al., 2014).

Rapid prototyping and the use of 3D printers:

- **Prototype production:** Students can quickly prototype their designs for testing and identify design flaws early on.
- **Design improvements:** Students can quickly produce prototypes using 3D printers and iteratively improve the design process.

Industry Collaborations and Real World Projects

Mechanical engineering education should be conducted in close collaboration with industry to support the implementation of innovations. Such collaborations allow students to put their theoretical knowledge into practice by engaging in real-world engineering projects. At the same time, students have the opportunity to develop solutions to problems faced by industry (Teixeira et al., 2020).

Industry collaborations and projects:

- **Industry-supported projects:** By working on engineering problems from real companies, students can develop creative solutions to industry issues.
- **Internships and field experience:** Through internships conducted in collaboration with industry, students can develop their engineering skills in real-world work environments.

Environmentally Friendly and Sustainable Designs

Sustainable engineering is an approach that aims to develop environmentally sensitive solutions and use resources efficiently. Mechanical engineering education should teach students to design by considering environmental impacts and encourage them to produce innovative solutions in this regard (Kalla & Brown, 2012).

Environmentally friendly design projects:

- **Renewable energy solutions:** Students create engineering designs using solar, wind, or other renewable energy sources.
- **Energy efficiency:** Students develop solutions to increase the efficiency of machines in order to save energy.

Innovative approaches such as Problem-Based Learning (PBL), Design Thinking, use of digital technologies, rapid prototyping processes, industry collaborations and sustainable design principles support students in developing creative solutions to engineering problems while also contributing to their awareness of social responsibility. Such pedagogical methods not only provide students with technical knowledge; they also enable them to gain the skills necessary to effectively solve engineering challenges they will face in the future. Innovative approaches combine theoretical knowledge with practical applications, contributing to students becoming more equipped engineers who act with sustainability and ethical responsibility.

CHALLENGES FACING INNOVATION IN EDUCATION

Innovation in education is a multifaceted process in which innovative methods, approaches and tools are used to enable individuals to have more productive and creative learning experiences. This process is not limited to the implementation of innovations alone; it also requires comprehensive strategic planning for sustainability, measurability and broad impact. The success of innovation in education depends on many factors, both internal and external. While some of these factors allow for the smooth implementation of innovative practices, others can complicate the process and negatively affect effectiveness.

The difficulties encountered when implementing innovation in education can be assessed in political, pedagogical, technological and socio-cultural dimensions. From a political perspective, instability in education policies, lack of long-term strategies and bureaucratic obstacles seriously hinder the spread of innovative methods. In particular, frequent changes in government policies and the failure to implement sustainable reforms make it difficult to create permanent and deep effects in the education system. In the pedagogical dimension, the competence of teachers in adopting and implementing innovative methods comes to the fore. Effective professional development programs and continuous education opportunities should be provided to teachers so that they can move away from traditional approaches and adapt to innovative pedagogies. In addition, the fact that current curricula are not compatible with innovative approaches and that traditional methods are still predominantly used in measurement and evaluation processes narrows the scope of these efforts (Fuad et al., 2022).

Technological infrastructure is also critical to the applicability of innovation in education. However, digital inequality, inadequacy of technological opportunities and unjust distribution of resources pose major obstacles, especially in developing countries. The integration of technology into education should not be limited to providing devices in classrooms; comprehensive planning is also required to ensure that these tools are used in line with pedagogical goals (Lira & de Souza, 2024).

The socio-cultural dimension has a significant impact on the applicability of innovation. The general attitude of society towards innovations, cultural resistance and the still strong presence of traditional values in education make it difficult to adopt these processes. In addition, the active participation of students, families and other stakeholders in these processes and their support for innovative approaches are critical for the successful implementation of innovation.

In conclusion, innovation in education does not only mean the implementation of new methods and tools; it also means a multidimensional transformation process that requires a strategic vision, a holistic understanding and effective cooperation among stakeholders. Multifaceted approaches should be adopted to overcome the challenges faced by this process and to restructure the education system with innovative reforms. The establishment of strong communication and cooperation mechanisms will open the doors to an effective transformation process among policy makers, education leaders and teachers.

Education Policies and Curriculum Barriers

Education systems are generally shaped by a long-term and organized structure based on traditional foundations. While this structure ensures the stable operation of the system, it also brings with it some obstacles that make it difficult to adapt to modern and innovative approaches. Since current curricula and education policies are mostly designed according to traditional pedagogical understandings and measurement-evaluation criteria, a more flexible system is needed for the integration of innovative teaching methods and technologies. However, the slow adaptation process inherent in education policies may prevent this transformation from taking place at the expected speed (Pak et al., 2020).

In order to effectively implement innovation in education, it is very important to reorganize curricula and policies to support innovative approaches. This restructuring requires not only content changes but also a review of teaching strategies, learning objectives and measurement-evaluation methods. For example, standardized tests and rote-learning teaching models commonly used in traditional systems are often inadequate in the face of innovative methods that are compatible with the goal of developing 21st century skills such as critical thinking, creativity and problem solving. Therefore, it should be considered a priority to provide education policies with a more innovative, dynamic and flexible structure (Khalil et al., 2023).

The process of adaptation of education systems to innovations is closely related to the speed of decision-making and implementation of education policies. Since policy-making processes often involve complex and bureaucratic structures that require the participation of many stakeholders, it can be difficult to quickly implement innovative practices. For example, many steps are required, such as making infrastructure investments for the integration of digital technologies into education, preparing educational programs for teachers to adapt to these technologies, and increasing social awareness. However, the fact that these processes require long-term planning can jeopardize the effectiveness and sustainability of innovation. In this context, it is not enough for education policies to focus only on meeting current needs; they must also prepare for future changes (Education et al., 2023).

It is vital at this point that policymakers adopt more flexible, forward-thinking and innovation-encouraging approaches. For example, effective strategies should be developed to incorporate modern teaching methods such as project-based learning, artificial intelligence-supported educational tools and game-based learning into the system. In addition, the success of innovative applications is not limited to decisions taken at the central level; detailed planning is also required to ensure the applicability of these decisions in local contexts.

As a result, the traditional and long-term structures of education systems present both opportunities and challenges in terms of the integration of innovative methods. Therefore, restructuring education policies and ensuring the active participation of all stakeholders in innovation processes are of critical importance. In order for innovation in education to be implemented sustainably, policies must be transformed into a dynamic, flexible structure that quickly adapts to changing needs.

a. Traditional Education Policies

Many educational systems are built on deep-rooted traditions and established norms that have developed throughout history. These systems are shaped around standardized curricula and teaching practices in line with educational policies determined in line with social values. While the traditional approach ensures that educational systems have a stable and orderly structure, it can make it difficult to adopt innovative teaching methods and technological tools. Standardized curricula limit flexibility by confining teaching processes to a rigid framework, and this poses a significant obstacle to change and transformation efforts in education.

Standardized curricula aim to provide a homogeneous learning experience, often ignoring students' individual learning needs and different pedagogical approaches. This restricts teachers' room to move toward innovative pedagogical methods or effectively integrate technology into educational processes. For example, modern teaching methods such as problem-based learning, project-based learning, or gamification require flexible curriculum structures. However, current standardized systems do not provide the space needed for such innovative approaches and pose a serious obstacle to innovation efforts in education (Adu et al., 2024).

Another important problem for innovation in education is the lack of academic freedom and flexibility. If teachers and educational leaders are not actively involved in decision-making processes, if innovative ideas are not encouraged, or if teachers' freedom in pedagogical practices is restricted, this significantly limits the impact of innovation initiatives. Lack of academic freedom not only limits teachers' capacity to develop creative approaches and implement methods that are appropriate for students' different learning needs, but also prevents the effective use of innovative technologies and educational tools.

Similarly, the integration of technological innovations into education often encounters resistance from traditional structures. For example, the use of technologies such as artificial intelligence-based learning platforms or digital content production may be limited due to existing infrastructure deficiencies and pedagogical vision deficiencies. The process of integrating these technologies into the curriculum requires steps such as training teachers, making radical changes in classroom practices, and providing the necessary resources. However, traditional structures are often inadequate in providing the support needed for this transformation (Singun, 2025).

In order to strengthen innovation in education, radical reforms in the system are inevitable. Making standardized curricula more flexible, increasing teachers' academic freedom and expanding their pedagogical areas, and integrating innovative technologies in line with pedagogical goals are the basic steps of this transformation. In addition, developing a strong collaboration and common vision among policy makers, teachers, students, and other stakeholders plays a key role in overcoming obstacles to innovation. Transforming education systems into a more flexible, creative, and innovative structure not only contributes to the development of individuals; it also increases the capacity to provide more effective solutions to social needs.

b. Lack of Flexibility in the Curriculum

The generally fixed, standardized and rigid structure of curricula makes it significantly difficult to implement innovative teaching strategies in education. In traditional education systems, the curriculum guides teaching processes by defining specific learning objectives, content areas and assessment methods in detail. However, this structure does not offer sufficient flexibility to teachers and educational institutions, thus restricting the implementation of innovative methods. In particular, the incompatibility of the current curriculum with innovative approaches in terms of pedagogy and content is one of the main problems that make it difficult for teachers to switch to these methods.

In order for innovative teaching strategies to be implemented effectively, the curriculum must have a more flexible structure and include content suitable for these strategies. However, traditional curricula generally adopt a linear approach focused on knowledge transfer. For example, innovative approaches such as project-based learning, the flipped classroom model or gamification aim to develop high-level skills such as critical thinking, problem solving and creativity. In contrast, standard curricula support a more rote-based learning and result-oriented system. This incompatibility makes it difficult to implement innovative methods because such methods may not match the limited time, content coverage and assessment criteria of traditional curricula (Hermansyah et al., 2025).

Teachers' inclination towards innovative strategies may be interrupted not only by the restrictive structure of the curriculum but also by the pedagogical difficulties that this situation causes. Since the curriculum provides a framework that guides teachers in the implementation process, an inflexible structure may make it difficult for teachers to try different methods. For example, if a teacher wants to implement a game-based learning activity with their students, this activity may delay the completion of the content specified in the curriculum or may not be compatible with standard assessment methods. Such restrictions may lead teachers to prefer traditional methods instead of innovative techniques.

The rigid curriculum structure makes it difficult not only for individual teaching practices but also for educational institutions to adopt innovative approaches at the institutional level. Innovation in education should not only be limited to individual teacher initiatives, but also should be systematically supported. However, the rigidity of existing curricula also makes it difficult for innovative strategies to be encouraged by educational policies and school administrations. This situation becomes especially evident in the implementation of new technologies and alternative teaching models. For example, if technologies such as digital learning environments or artificial intelligence-supported tools are not compatible with the content structure and assessment methods of the standard curriculum, the integration of these innovations into educational processes may not be possible.

In order to enable innovation in education, it is vital that curricula become more flexible, open to innovation and dynamic. In order to ensure this transformation, an inclusive approach that ensures the active participation of teachers, students and other stakeholders in curriculum development processes should be adopted. In addition, a curriculum approach that prioritizes not only knowledge transfer but also skill acquisition and value creation should be created. With the realization of this transformation in education systems, teachers and educational institutions can more easily adopt and implement innovative methods. In this way, students will have the opportunity to prepare more effectively for rapidly changing world conditions.

Teacher Education and Competence Issues

Innovation in education is a multifaceted and complex process that is not limited to the integration of technological tools into the classroom or the implementation of new teaching methods. In this process, it is essential for teachers to develop their knowledge and skills in order to effectively use innovative approaches in line with pedagogical goals. The successful implementation of innovation in education requires teachers to increase their competence in integrating these applications into classroom practice (Alkharusi, 2012).

However, teachers' current knowledge and competencies may be insufficient to adapt to innovative approaches. This situation not only limits the effectiveness of innovative practices, but can also negatively affect the overall quality of education. One of the most important difficulties teachers face in adapting to innovation is their lack of pedagogical and technological knowledge. Many teachers have received training in traditional educational approaches and developed their professional experience within the framework of these methods.

In this context, innovative teaching strategies and effective use of digital tools imply a new skill set for teachers that needs to be developed both technically and pedagogically. For example, the implementation of AI-based learning platforms, virtual reality tools or game-based learning approaches requires not only technological knowledge but also an understanding of how to use these tools effectively pedagogically. Lack of this knowledge and understanding may reduce teachers' motivation to adopt innovative practices or lead to ineffective use of these practices.

In addition, the lack of support mechanisms for teachers to be included in innovation processes further increases the complexity of the process. The successful adoption and implementation of innovative practices is possible not only with individual efforts but also with continuous professional development programs and supportive policies to be provided at the institutional level. However, current professional development programs mostly focus on traditional pedagogies and do not include technology and methodology training for innovation. This deficiency can negatively affect teachers' self-confidence and perception of competence in effectively implementing innovative approaches.

Teachers' adaptation to innovation is also greatly affected by their individual awareness and motivation levels. Continuous learning and being open to change are critical to the adoption of innovative methods and tools. However, teachers' heavy workloads and time constraints can make this process difficult. For example, a teacher under pressure to complete a tight curriculum may have difficulty dedicating time to the additional learning and preparation processes required for the integration of digital tools or the implementation of a new teaching methodology. Such difficulties may result in innovative approaches being implemented only superficially, limiting their impact in the classroom.

In order to achieve sustainable innovation in education, comprehensive support mechanisms for teachers must be established. In this context, continuous professional development programs that aim to increase teachers' pedagogical and technological knowledge play a critical role. However, these programs should not be limited to the introduction of new tools and technologies. At the same time, they should provide practical guidance on how to use these tools in a way that suits student needs. In addition, policies that encourage teachers' active participation in professional development processes should be developed to increase their motivation for innovative practices.

As a result, the inadequacy of teachers' current knowledge and skill levels in adapting to innovative practices is one of the main obstacles to innovation in education. In order to overcome this obstacle, comprehensive support programs and continuous professional development opportunities should be provided, and at the same time, an educational culture open to innovation should be built. Education systems should adopt structural and political arrangements that will help teachers adapt to this transformation process. In this way, the benefits of innovation in education can be demonstrated more effectively and significant contributions can be made to the quality of education.

a. Inadequate Professional Development

The majority of teachers have extensive knowledge and experience with traditional teaching methods. These methods have shaped teachers' pedagogical habits over the years and have provided predictability and convenience in educational processes. However, effective implementation of innovation in education requires teachers to adapt to innovative teaching strategies and develop their skills to work with these strategies. The success of this process is possible not only with individual efforts of teachers, but also with structured programs that continuously support their professional development. Therefore, investing in the professional development of teachers plays a critical role in the success of innovation in education (Brouwer et al., 2012).

Traditional methods generally adopt a teacher-centered approach that focuses on knowledge transfer. Although this model provides pedagogical convenience, it is insufficient to meet today's educational needs. Innovative teaching strategies include approaches that include student-centered learning, project-based learning, the flipped classroom model, and the integration of digital tools. These strategies aim not only to transfer knowledge, but also to provide high-level skills such as critical thinking, problem solving, collaboration, and creativity. Therefore, in order for teachers to effectively implement such methods, both their pedagogical knowledge and technological competence need to be updated.

In current education systems, the inadequacy of professional development programs offered to teachers is a significant obstacle to this transformation process. Many education systems lack a structure that supports the continuous and comprehensive development of teachers. Current programs mostly focus on traditional pedagogies and do not provide sufficient guidance on innovative practices. For example, when sufficient information and application support are not provided on the use of digital technologies in the classroom or game-based learning, teachers may have difficulty adopting these techniques. This deficiency may cause innovative approaches to remain at a superficial level and the expected transformation not to occur.

Professional development programs should not only be based on knowledge transfer, but also include practical learning opportunities. Research shows that teachers' knowledge and skills regarding innovative strategies develop more effectively through direct experience and practice. For example, the effective use of methods such as game-based learning or the flipped classroom model is possible when teachers experience these approaches in the classroom. However, many professional development programs do not provide teachers with sufficient practice opportunities. This situation can negatively affect teachers' motivation for innovative approaches.

Teachers' participation in professional development processes can be limited by practical obstacles such as cost, time constraints, and lack of infrastructure. Intensive curriculum programs can make it difficult for teachers to allocate time to professional development activities. In addition, lack of access to technological devices and technical support can reduce the efficiency of training on the use of digital technologies. Overcoming such obstacles requires professional development programs to be more accessible and sustainable. For example, organizing programs on how to use digital tools in the classroom can facilitate the transformation process by providing teachers with both theoretical knowledge and practical support.

In order to encourage innovation in education and ensure teachers' integration with innovative methods, professional development programs should have a comprehensive, continuous and supportive structure. These programs should aim not only to provide teachers with knowledge and skills, but also to instill self-confidence in applying these methods in the classroom environment. It is of great importance for educational leaders and policy makers to develop strategies that prioritize teachers' professional development and to ensure teachers' active participation in this process. In order for innovative teaching strategies to be successfully implemented, investments in teachers' professional development should be increased. Such investments not only improve teachers' individual skills; they also increase the overall quality of education, allowing students to acquire skills appropriate to the requirements of the age. Transforming education systems to adapt to changing pedagogical needs will make significant contributions to the effective implementation of innovation in education and to achieving positive results at the societal level.

b. Resistance and Fear of Change

One of the biggest obstacles to innovation in education is the resistance that teachers show to change. This resistance is caused by a combination of individual, professional and systemic factors and makes it difficult for teachers to abandon traditional methods that they have become accustomed to. Traditional teaching methods have been used for many years and offer teachers a comfort zone and predictability in terms of pedagogy.

However, abandoning these methods can be perceived as a time-consuming, complex and even risky process for teachers. Professional habits and pedagogical self-confidence in particular play an important role in resistance to change. Teachers who have worked within a certain teaching model for many years may have more difficulty in the process of adapting to innovative technologies and methodologies.

Teachers' resistance to change can sometimes lead them to completely reject innovative practices or to adopt them only superficially. Research shows that it is critical to clearly explain the reasons for change and the potential benefits to teachers during this adaptation process. However, in many cases, teachers do not receive sufficient guidance and support during this process. In addition, the perception that innovative practices require more time and effort can increase resistance to change. Teachers, especially those working under heavy curriculum loads, may not be able to reconcile the preparation process required for planning and implementing these applications with their current workload. For example, effective use of digital learning tools requires teachers to develop technical skills and integrate these tools in a pedagogically appropriate way. This process forces teachers to reconsider their professional skills and can create additional pressure, making it harder for them to embrace change.

One of the main reasons why teachers resist change is the inadequacy of the support mechanisms required for the effective implementation of innovative practices. It is clear that teachers need institutional and systemic support in addition to their individual efforts in innovation processes. However, such support structures are not sufficiently included in many educational institutions. In particular, elements such as professional development programs, technological infrastructure and mentoring are often neglected. This situation causes teachers to feel alone in the face of change and to be inadequately prepared.

In addition, the inadequacy of school leaders and policy makers in encouraging innovative processes can negatively affect teachers' motivation. Teachers' resistance to change not only slows down the implementation of innovation, but can also lead to significant disruptions in students' learning processes. Ineffective use of innovative teaching methods and technologies can prevent students from developing 21st century skills such as critical thinking, problem solving and collaboration. In addition, an educational environment closed to change can reduce the quality of learning by reducing student motivation and participation in class.

Priority should be given to awareness-raising activities to reduce teachers’ resistance to change. Explaining the potential benefits of innovative approaches in education to teachers can make it easier for them to accept change. In addition, continuous and comprehensive professional development programs should be used to support teachers' adaptation to new technologies and methods. These programs should not be limited to knowledge transfer; they should also aim to increase teachers' self-confidence by providing them with practical learning opportunities.

Creating a collaborative learning community is also important in this process. In this way, teachers can share their experiences and learn from each other, increasing their confidence in the change process. In addition, school leaders and policy makers should take a determined stance to guide teachers and develop policies that encourage change in order to support innovative processes.

Teachers' resistance to change is one of the main obstacles to innovation in education. Overcoming this obstacle is possible not only with the individual efforts of teachers, but also with the comprehensive support and guidance provided by all stakeholders in the education system. Establishing a collaborative structure between educational leaders, policy makers and teachers will reduce resistance to change and ensure that innovation is implemented more effectively in the educational environment. Such a transformation will make significant contributions to the quality of education by improving the learning processes of both teachers and students.

Technological Infrastructure and Access Challenges

The inclusion of technology in educational processes is one of the most important steps of innovation in education. Digital devices have the power to improve learning spaces, facilitate teaching methods and better respond to students' personal learning desires. In this case, new teaching methods are usually supported by technologies such as digital tools; online spaces, simulations; augmented reality (AR), artificial intelligence (AI) and learning management systems (LMS). However, the inclusion of these tools in educational institutions and their effective use face many challenges. These challenges are; These problems range from lack of technology infrastructure to educators' digital competencies, from insufficient financial resources to political and cultural barriers. In order for technology to be used effectively in educational institutions, a strong technology infrastructure is essential. However, especially in developing countries and rural areas, basic elements such as internet connection, hardware access, and technical support are often inadequate. For example, low-bandwidth internet connections can limit the use of online platforms, while old or poorly developed devices can prevent the effective application of digital tools (Arar et al., 2023).

Likewise, the maintenance and update processes required for the sustainable use of technology are often neglected. This situation disrupts the integration of technology into educational environments not only at the initial stage but also in the long term. In order for technology to be used successfully in education, infrastructure alone is not sufficient; developing the digital skills of teachers and students is also of critical importance. In order for teachers to use digital tools effectively in a pedagogical context, both technical knowledge and pedagogical application knowledge are required. However, many teachers have limited opportunities to develop their digital competencies.

Research shows that professional development programs often focus on the basic use of technological tools, but do not focus enough on the pedagogical integration of these tools. This can lead to teachers using innovative technologies superficially and not fully benefiting from the potential of these technologies in education. The integration of technology in education requires significant financial resources. Processes such as purchasing technological devices, obtaining software licenses, establishing infrastructure, and training staff are often costly. However, many educational institutions do not allocate sufficient budgets for such investments. Especially in low-income regions, a large portion of the limited resources allocated to education are directed to basic needs, while technological investments remain in the background. This situation can increase inequalities in education and cause the digital divide to widen.

Attitudes and policies towards the use of technology in education are also among the important factors affecting the integration process. In some educational systems, skepticism towards technology or strong commitment to traditional teaching methods can make it difficult to adopt digital tools. In addition, the fact that policymakers and school leaders do not see technology as a strategic tool can hinder innovative initiatives in this area. In addition, negative perceptions of students and parents towards the use of technology can create additional difficulties in this process. For example, concerns that excessive use of digital tools may cause distraction in students or weaken face-to-face communication may delay the acceptance of technology in the classroom environment. The role of technology in education may be limited when evaluated only from an instrumental perspective. Digital technologies have the potential to individualize students' learning processes, make learning more accessible, and provide interactive learning environments. However, realizing this potential depends on technology being evaluated not only as a tool but as a pedagogical solution. For example, artificial intelligence-supported learning platforms can provide significant improvements in learning outcomes by offering content customized to students' individual learning needs. However, using such platforms without pedagogical foundations may limit the expected benefits. These difficulties encountered in the integration of technology in education should be addressed with solution-oriented approaches. First of all, developing the technological infrastructure of educational institutions and providing comprehensive professional development programs for teachers are the basic steps for the success of this process. In addition, policy makers and education leaders need to adopt technology as a strategic innovation tool in education and develop long-term plans in this direction. Awareness-raising studies on the use of technology in education can positively affect the attitudes of students, teachers and parents towards this process. Finally, prioritizing schools, especially in disadvantaged regions, to ensure equal opportunities in education can contribute to closing the digital gap.

In conclusion, the role of technology in education is an indispensable component in the implementation of innovative teaching methods. However, the success of this process depends on the adoption of technology not only as a tool but also as a pedagogical value. Transforming education systems to support the use of technology will ensure the effective implementation of innovation and the improvement of the quality of education.

a. Technological Access and Infrastructure Issues

The integration of technology in education stands out as a significant obstacle, especially in low-budget schools and developing regions. Inadequate technological infrastructure makes it difficult for both teachers and students to use innovative learning tools effectively, and this situation further deepens inequalities of opportunity in current education (Brenya, 2024). Limitations in access to necessary technological tools widen the digital divide and have negative effects on learning outcomes. The basis of this problem is lack of financial resources, lack of infrastructure development projects and sustainability problems. Many low-budget schools lack basic tools that can effectively use technology in education. The lack of devices such as computers, tablets or smart boards makes it almost impossible to benefit from digital teaching materials (Linhalis & da Silva, 2023). In addition, even in institutions where these devices are available, old or inadequate equipment can prevent students from developing digital skills or limit this process. For example, in schools with limited computers, the fair and efficient use of these devices becomes quite difficult. The shortening of students' access to technology, especially in crowded classes, negatively affects individual learning processes. A reliable and fast internet connection is essential for the successful use of digital tools in education. However, in many developing regions, the internet is either completely non-existent or has severely limited access due to low speeds and high costs. In rural areas in particular, the lack of internet infrastructure makes it impossible to benefit from online education platforms or digital content. This not only prevents the full potential of digital technology-based teaching methods from being fully utilized, but also creates significant inequalities in access to information between students and teachers. Research clearly shows that students without internet access are at a disadvantage in terms of both academic achievement and digital skills.

The establishment and sustainability of technological infrastructure requires serious costs. Low-budget schools generally do not have sufficient financial resources to make such investments. The limited public funds provided to educational institutions prevent the provision of the necessary resources for technology integration. In addition, additional expenses such as software licenses required for the use of technology, maintenance and repair costs of devices, and technical support services are neglected due to budget constraints. This situation also brings with it long-term sustainability problems and prevents the effective use of technology in education. Inequalities in access to technological infrastructure further deepen the long-standing inequalities of opportunity in education. Today, access to technology provides a significant advantage for students in terms of accessing information, acquiring digital skills, and preparing them for the future labor market. However, students, especially those studying in low-budget schools, are deprived of these opportunities and experience serious difficulties in adapting to the digital world. For example, students who cannot access digital tools are deprived of individual learning processes, and this also limits the development of basic competencies such as critical thinking and problem-solving skills. Such limitations not only lead to failure at the individual level, but can also have consequences that undermine the ideal of social equality.

In this context, it has become a necessity to develop effective policies and practices to eliminate technological infrastructure deficiencies and ensure equal opportunities in education. First, there is a need for special technology grants and financing models designed for low-budget schools. Such a financing mechanism can allow basic requirements such as computers, tablets, internet connections and software licenses to be met. In addition, collaborations between the public and private sectors are among the applicable strategies to strengthen the technological infrastructure of educational institutions. Second, infrastructure investments to eliminate internet access problems are of critical importance. In order for individuals living in rural and disadvantaged areas in particular to have low-cost, high-speed and reliable internet service, governments and relevant organizations need to expand broadband infrastructure. In this context, alternative solutions such as satellite technologies or mobile networks can also be considered as effective tools for low-income regions. Third, professional development of teachers should be supported to eliminate digital inequality. Digital skills programs for teachers are important in terms of effectively integrating technology into the classroom environment. In parallel, students should be provided with training in digital literacy to encourage them to operate successfully in the digital environment. The inadequacy of technological infrastructure is one of the main obstacles that seriously limits the innovation capacity of the education system. This problem has a profound negative impact not only on individual learning processes but also on equal opportunities in education. However, strategic initiatives in this area can make significant contributions to the construction of a more equitable and innovative education ecosystem by closing the digital gap. In the long term, such initiatives will enable a transformation that can form the basis for the sustainable development of both individuals and societies.

b. Digital Literacy Problems of Students and Teachers

In order for digital tools to be used effectively in education, it is of great importance for teachers and students to reach a certain level of digital literacy. Digital literacy is the ability of individuals to understand and use digital technologies and to integrate them effectively in their lives and educational processes. However, effective use of digital tools can be difficult for those who do not have this skill. Especially teachers who are accustomed to more traditional education methods cannot fully evaluate the opportunities offered by digital tools and sometimes they may experience a lack of motivation to use these tools. Traditional education methods include a structure in which the teacher actively transfers information in the classroom, while students are generally passive recipients. Digital technologies, on the other hand, increase interaction and offer tools that can customize learning according to students' own pace and interests. This transition requires teachers to move away from the methods they are accustomed to and can often create a feeling of inadequacy in using digital tools (Fernández-Batanero et al., 2021).

On the other hand, students with low digital literacy may also have difficulty using these tools effectively. Digital literacy includes not only the ability to use technology, but also important concepts such as online security, access to information and evaluating accuracy, and digital ethics. While students who can use technology effectively can have a more interactive and personalized experience in classes, students with low digital literacy may have difficulties in obtaining healthy information from online sources or using technological tools in line with educational goals.

As a result, teachers should be provided with training and development opportunities to increase their digital literacy. Similarly, students should be provided with digital literacy training so that they can use technology not only as consumers but also as producers. The innovation process in education should be continuous so that teachers can adapt to technology and students can effectively navigate the digital world. Otherwise, the opportunities provided by digital tools cannot be fully utilized and the success of innovative developments in education will be prevented.

As a result, digital literacy is a factor that directly affects success in education. The potential of digital tools in education can be realized in the best way when teachers and students are provided with the necessary training and support to use the digital world more effectively. Proper management of this transition is one of the fundamental elements that will determine the success of the innovation process in education.

Financial Restrictions

Innovation in education is a process that generally requires high levels of financial resources and long-term investments. This process includes elements such as technological infrastructure investments, teacher training, digital platforms, software, and new teaching methodologies. However, the vast majority of educational institutions do not have sufficient financial resources to cover such investments. This situation constitutes a significant obstacle to the spread and permanence of innovative approaches in education.

a. Inadequacy in Education Budgets

The fact that education budgets are generally limited stands out as one of the most important obstacles to innovation. Educational institutions have to make significant financial investments in areas such as establishing the technological infrastructure required to innovate teaching methods, organizing professional development programs for teachers, and creating digital resources. However, most of the time, since the budgets allocated for such investments are tried to be balanced with the other needs of the institutions, sufficient resources are not allocated to innovative projects. This situation is not limited to the lack of technological infrastructure; it also causes financial investments for the professional development of teachers to remain in the background. As a result, the innovation process may be delayed or stalled.

b. Short Term Budgeting Approaches

Many education systems adopt approaches that aim to achieve short-term goals through annual budgets. These budgeting strategies are generally designed to produce solutions for urgent needs in education, and long-term investments such as the implementation of innovative changes are often not given priority. Innovative transformations in education are long-term processes, and the positive results of these processes begin to appear over time. However, education policies and budgeting processes often address the necessity and impact of such changes within the framework of an approach that can be measured and evaluated in the short term. This often causes investments in innovative projects to be postponed, thus preventing a sustainable development process.

In summary, financial constraints to innovation in education stem from both short-term budgeting approaches and limited resources. These barriers can result in the innovation process being blocked or slowed down, making it harder for educational transformation to occur and spread effectively.

Cultural and Social Barriers

Innovation in education can face not only individual or institutional barriers, but also cultural and societal barriers. Educational systems are often deeply connected to the cultural values, traditional norms and social structures of societies. This can make it difficult to accept and implement innovative educational changes. Societies' understandings of education are often deeply rooted in the past, and these understandings may be intertwined with societal norms and values that have been shaped over many years. Therefore, innovative approaches in education may clash with these deep-rooted structures and encounter societal resistance.

a. The Impact of Traditional Educational Approaches

In many societies, education is often based on certain traditions. These traditions can have a wide range of effects, from teaching methods to examination systems, from course content to teacher-student relationships. When innovations in education come into conflict with these deep-rooted traditions, social resistance may be inevitable. For example, in some societies, there is a strict adherence to the authority of teachers, teaching materials, and classroom discipline. Innovative changes, such as new, student-centered teaching methods or the use of digital learning tools, may be perceived as disrupting this traditional structure. This may lead to a social reaction and make it difficult to accept the change.

b. Social Values and Norms

Education not only equips individuals with knowledge, but also reinforces the values and norms of societies. Therefore, any innovation in education should be sensitive to social values and cultural context. For example, in some cultures, the treatment of certain subjects or the application of certain teaching methods may conflict with social values. Societies expect education systems to maintain cultural transmission between generations and to ensure social order. In this context, innovations that ignore social norms and cultural values may not be accepted and may encounter resistance. At the same time, lack of social awareness about changes in education may reinforce these obstacles.

c. Inequality and Social Hierarchies in Education

In some societies, inequalities in education and social hierarchies can also be important factors that hinder innovation. Education can function as a field where power relations between social classes and different groups are reproduced. Innovation in education can be perceived as a process that will shake these power structures and threaten the interests of certain groups. For example, digitalization and greater integration of technology in education can create a more accessible learning environment for low-income groups. However, people in higher-income groups may resist innovations because of concerns that this change may threaten their social position. Innovative initiatives aimed at eliminating inequality in education in society aim to transform these deep inequalities in the social structure, but the response to these changes can be shaped by social Dynamics (Abdullah & Manning, 2011).

d. Social Reflections of Education Policies

Innovations in education are not only related to changes in education policies, but also to the reflections of these policies at the societal level. Education reforms may aim to transform inequalities based on gender, ethnicity, age and other social factors. However, in some societies, such reforms may be perceived as threatening to social and cultural structures. Especially in traditional social structures, innovative steps in issues such as women's education or the educational rights of minority groups may encounter widespread social resistance. Such resistance can slow down the innovation process and prevent the successful implementation of innovations (Chima Abimbola Eden et al., 2023).

e. Social Acceptance and Participation in Innovation in Education

Achieving success in the implementation of educational innovations depends significantly on social acceptance and active participation. This process is influenced not only by the policies enacted by governments or educational institutions but also by the perceptions and attitudes of various societal groups toward these innovations. A society's openness to change plays a crucial role in determining how quickly and effectively these advancements are embraced. Therefore, fostering social awareness becomes a pivotal step in ensuring the widespread and effective adoption of innovations within the education sector (Vasquez-Martinez et al., 2013).

Generating widespread awareness about innovative educational methods and fostering social support are crucial for the successful adoption of change. However, educational innovation often faces challenges arising from cultural and societal barriers. Traditional values, norms, and social frameworks within communities can influence the acceptance of educational reforms. For this reason, any innovative initiative must be thoughtfully designed with careful attention to the social context. Addressing these obstacles requires education policies that align with societal realities, efforts to build public awareness, and the active involvement of all stakeholders in the process (Nurutdinova et al., 2016).

FUTURE DIRECTIONS AND INNOVATION

In the future, innovation in education will not be limited to technological developments; it will also interact deeply with the transformation of social structure, labor markets, and education policies. Innovative approaches in the education system will be reshaped in parallel with the rapidly changing digital environment, the transformation of social needs, environmental sustainability principles, and modern workforce expectations. In this context, the opportunities offered by technology, social responsibility awareness, individualized education models, sustainability-oriented goals, and structured teaching approaches in line with workforce demands will stand out as the cornerstones of innovations in education in the future (Milhaleva, 2020).

The Place of Technological Developments in Education

Technology will continue to be the most fundamental driver of innovation in education. However, future technological transformations will not only be limited to teaching materials and tools; they will also deeply affect and reshape students' learning methods and teachers' pedagogical approaches. Artificial intelligence will play a critical role in providing personalized learning experiences. Teaching tools supported by artificial intelligence can analyze individual students' learning speed, preferences, and needs, and provide content recommendations and feedback accordingly.

In addition, thanks to learning analytics, students' performance can be continuously monitored, early intervention systems can be developed, and educational processes can be made more efficient. Thus, it will be possible to provide students with a more focused and effective educational experience. Advanced technologies such as virtual reality (VR) and augmented reality (AR) will bring more interactive, visualized, and experience-oriented learning environments to education. These innovations will offer a new learning process in which students combine both theory and practice by examining complex engineering systems, machine designs, or various simulations in a virtual environment.

Especially in fields with high application intensity such as mechanical engineering, such technologies will create groundbreaking effects in prototyping and simulation processes. With the impact of technology on education, blended learning and distance education platforms are expected to become more widespread. Students will have a more flexible learning experience by combining traditional face-to-face education processes with online learning materials and digital classrooms. Considering that distance education technologies have undergone a significant evolution, especially after the COVID-19 pandemic, it is understood that virtual classrooms and time- and space-independent learning opportunities will now be preferred more.

Personalized Learning and Individualized Education

The future of the education system will be based on an understanding that will be restructured in accordance with the individual needs of each student. In this context, personalized learning approaches will focus on content adapted to each individual's learning speed, interests and learning styles. This process will become more efficient and dynamic thanks to the effective use of technology. Advanced technological tools allow adaptable learning systems to continuously monitor students' learning processes.

These systems can organize the curriculum for students in line with their individual needs; thus, allowing students to practice more in areas where they are strong, while providing additional resources and applications in areas where they are weak. Such an approach aims to present the learning experience in a format that is both flexible and targeted.

In addition, in the coming years, teachers will be able to design more interactive, creative and engaging content for students with technology-supported methods. The use of innovative methods such as game-based learning applications, interactive simulations and storytelling will increase students' motivation for lessons and carry their learning processes to more permanent and meaningful dimensions.

Sustainability and Social Responsibility in Education

The education systems of the future will not only be limited to individual success but will also prioritize the principles of social responsibility and sustainability. Innovation is aimed to lead to sustainable effects in environmental, social and economic dimensions. Green education will be shaped by the integration of environmental sustainability and nature-friendly technologies into the education process. Students will be developed with projects that provide not only engineering and technology but also social responsibility awareness and environmental awareness.

These projects will support students in gaining sensitivity to the environment and developing their solution-oriented thinking skills. Innovations in education will progress with an approach that is sensitive not only to technology but also to fundamental values such as social equality, cultural diversity and human rights. More inclusive and diversified education models will be designed to ensure that every student has equal opportunities. Students will be raised with an educational approach that encourages understanding different cultures, languages and social structures.

Workforce and Talent Development Focused Training

Another critical dimension of innovation in education is the systematic development of skills that are appropriate for the dynamic needs of the labor market. Today's rapidly changing business world requires students to go beyond providing them with purely theoretical knowledge; instead, it requires them to be equipped with multifaceted competencies such as practical skills, social competencies, and critical thinking. In the coming years, collaborations between educational institutions and industrial organizations are expected to increase significantly. In this context, it will be important for students to participate more effectively in real-world projects and to integrate them into educational programs designed for the industry (Sarvi & Pillay, 2015).

Practical-oriented educational processes such as internships, field experiences, and industrial projects ensure that students are better prepared for the challenges they will face in the labor market. However, the future workforce is not expected to be content with only technical skills; they also need to have critical soft skills such as communication, leadership, teamwork, and problem solving. In this context, innovative approaches in education should prioritize not only strengthening academic competencies, but also providing individuals with such skills for their professional and personal development (Ali & Khushi, 2018).

Global Education Trends and Mobility

Factors such as international collaborations, digitalization, and student mobility will enable education systems in different regions to mutually influence each other and will create common innovation trends around the world. In turn, innovation in education will create an effective transformation at the global level. Digitalized education platforms will provide students with the opportunity to connect with schools in various regions of the world, exchange information, and discover educational approaches of different cultures. International online courses, digital certification programs, and virtual student exchange projects will make global education opportunities more accessible than ever before (Marchenko et al., 2021).

One of the main goals of innovation in education is to increase accessibility. Digital platforms, distance learning opportunities, and open source content will provide more equitable and inclusive education opportunities for students around the World (Haleem et al., 2022). In this way, it will be possible to provide quality education opportunities, especially to students in developing regions. Innovations in education in the future will be shaped by both technological advances and social needs.

Artificial intelligence, virtual reality, personalized learning, and social responsibility concepts will form the basis of these innovative approaches. In addition, factors such as workforce dynamics, industry collaborations and global education trends will play a critical role in the development of education systems. These transformations will aim to provide students with a more effective, inclusive and sustainable learning experience, while leading to an approach that will develop them as future leaders.

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AI-Based Anomaly Detection for Operational Continuity in Mining and Energy Sectors

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ABSTRACT

The mining and energy industries are undergoing a profound digital transformation, characterized by the integration of Cyber-Physical Systems (CPS) and the Industrial Internet of Things (IIoT). In these sectors, operational continuity is paramount, as equipment failures or system anomalies lead to significant economic losses and environmental risks. However, the vast streams of data generated by industrial assets are inherently noisy, high-dimensional, and non-stationary, rendering traditional statistical monitoring methods insufficient.

This book chapter provides a comprehensive exploration of Artificial Intelligence (AI) based anomaly detection as a strategic tool for enhancing reliability and safety. The study examines sector-specific applications, ranging from the predictive maintenance of heavy mobile equipment using Long Short-Term Memory (LSTM) networks in mining and energy to the monitoring of smart grids and renewable energy assets using Convolutional Neural Networks (CNN) and Graph Neural Networks (GNN). Beyond algorithmic selection, the chapter addresses critical implementation challenges, such as data veracity in harsh environments, the necessity of Edge AI for real-time processing, and the role of Explainable AI (XAI) in fostering operator trust through transparent decision-making. By synthesizing current methodologies with a vision for Digital Twins and self-healing systems, the discussion highlights how AI-driven insights are shifting heavy industry from reactive maintenance paradigms toward a proactive, autonomous future. This work serves as a technical roadmap for researchers and engineers seeking to leverage deep learning for anomaly detection in complex industrial ecosystems.

Keywords – Anomaly Detection, Industry 4.0, Predictive Maintenance, Deep Learning, Mining Industry, Energy Systems, Digital Twin, Explainable AI.

INTRODUCTION

In the modern industrial paradigm, mining and energy facilities have evolved beyond traditional physical production units into what are now recognized as "Digital Data Factories", where data serves as the primary raw material. At the heart of this transformation lies Industry 4.0, which advocates for the autonomization and vertical-horizontal integration of production processes; heavy industries such as mining and energy constitute the most critical application areas for this transition (Lasi et al., 2014). In particular, the Industrial Internet of Things (IIoT) establishes a massive network structure where every sensor, actuator, and machine on-site is interconnected (Boyes et al., 2018).

These facilities are now defined as Cyber-Physical Systems (CPS). CPS are integrated systems where physical processes are monitored and controlled by computing and communication units, interacting through continuous feedback loops (Monostori et al., 2016). Autonomous truck fleets in mining or smart load-balancing systems in energy grids are tangible examples of this cyber-physical integration. However, this integration creates a level of complexity in terms of the velocity, volume, and variety of data that surpasses the capacity of traditional analytical methods (Zhou et al., 2015).

The "Big Data" chaos in heavy industry is not merely a matter of data volume but is also deeply related to the "Veracity" (Uncertainty) dimension of the data. Extreme conditions such as heavy dust and high electromagnetic interference in mining sites, or extreme temperatures in power plants, cause data from IIoT sensors to be noisy and incomplete (Tao et al., 2018). This situation represents the primary structural barrier to generating meaningful anomaly signals from raw data. Consequently, the literature indicates that Deep Learning based approaches are increasingly replacing traditional Statistical Process Control (SPC) methods to manage this chaotic data stream (LeCun et al., 2015).

In the energy sector, data dynamics have become even more complex with the integration of renewable sources. Smart Grids must manage bidirectional flows of both data and energy, making the system more vulnerable to external cyber-attacks and instantaneous imbalances (Gungor et al., 2011). In this context, anomaly detection is not just a performance parameter but also a fundamental line of defense for national security and grid resilience (He & Yan, 2016).

Within this technological ecosystem, Digital Twin applications in the mining and energy industries represent the pinnacle of operational intelligence. By merging real-time data from physical assets with high-fidelity simulation models, these structures offer the capability to foresee potential failure scenarios and anomalous conditions before they occur (Kritzinger et al., 2018). This evolution leaves traditional reactive maintenance strategies behind, paving the way for proactive and autonomous decision-support mechanisms where the system monitors itself (Wuest et al., 2016). Thus, the chaotic nature of data is transformed into a controllable and predictable operational advantage through artificial intelligence.

AI-DRIVEN ANOMALY DETECTION IN MINING OPERATIONS

Mining operations are characterized by high-risk environments and capital-intensive assets, where even minor operational deviations can escalate into catastrophic failures or significant economic losses. The transition from traditional monitoring to AI-driven anomaly detection has enabled the industry to move toward a "zero-harm" and "zero-downtime" objective.

Predictive Maintenance for Heavy Mobile Equipment: The Role of LSTM

The most significant operational cost in open-pit mining is often attributed to the maintenance of heavy mobile equipment (HME), such as ultra-class haul trucks and hydraulic shovels. These machines generate high-frequency time-series data from hundreds of engine, transmission, and hydraulic sensors.

Traditional threshold-based alarms fail to capture the subtle, long-term degradations that precede a major engine failure. This is where Long Short-Term Memory (LSTM) networks, a specialized form of Recurrent Neural Networks (RNNs), prove superior. Unlike standard neural networks, LSTMs can retain information over long sequences, making them ideal for detecting "lead-time" anomalies in sensor data (Hochreiter & Schmidhuber, 1997). For instance, an LSTM model can analyze a 48-hour window of oil temperature and pressure fluctuations to predict a cooling system failure that a simple limit-switch would miss until the moment of breakdown (Zhao et al., 2019).

Processing Plant Optimization and Deviation Detection

In mineral processing plants (concentrators), the goal is to maintain a steady state in crushing, grinding, and flotation circuits. However, ore variability and mechanical wear introduce "process anomalies" that reduce recovery rates.

To detect these deviations, Isolation Forest and Autoencoder models are frequently employed. Isolation Forests work on the principle of "isolating" anomalies rather than profiling normal points, which is highly effective in high-dimensional processing data (Liu et al., 2008). Alternatively, Autoencoders (a type of unsupervised deep learning) learn to compress and reconstruct "normal" process data. When a sensor drift or a blockage occurs in a flotation cell, the "reconstruction error" increases significantly, flagging the event as an anomaly (Kramer, 1991). This allows metallurgists to intervene before the final product grade is compromised.

Safety and Environmental Monitoring: Seismic and Gas Detection

Beyond equipment, anomaly detection is a critical tool for Occupational Health and Safety (OHS). In underground mining, detecting anomalous patterns in seismic activity and gas concentrations (CH4, CO) is vital for preventing rockbursts and explosions.

Integrating AI with fiber-optic sensing and micro-seismic arrays allows for the real-time detection of "pre-seismic" patterns. Machine learning models can distinguish between routine blasting and genuine geomechanical anomalies, reducing false alarms while providing early warnings for potential tunnel collapses (Wong et al., 2020). A synthesis of common data sources, identified anomaly patterns, and the associated operational risks in mining environments is categorized in Table 1.

Table 1: Data Sources, Potential Anomalies, and Operational Risks in Mining Sectors

Industry	Data Source	Potential Anomaly	Operational Risk
Mining	Vibration Sensors	Unexpected harmonic frequency increase	Bearing or gear failure (Mechanical breakdown)
Mining	Gas Sensors	Sudden methane (CH4) concentration slope	Explosion risk and OHS (Occupational Health/Safety)

AI-DRIVEN ANOMALY DETECTION IN THE ENERGY INDUSTRY

The energy sector is undergoing a dual transformation: the digitalization of aging infrastructure and the rapid integration of intermittent renewable energy sources. In this context, anomaly detection serves as the "immune system" of the grid, identifying cyber-threats, equipment failures, and supply-demand imbalances in real-time.

Smart Grids and Consumption Anomalies

Smart grids rely on bidirectional communication between utilities and consumers. However, this connectivity introduces vulnerabilities. Anomaly detection in smart grids primarily focuses on Non-Technical Loss (NTL) detection, which includes electricity theft and meter malfunctions.

Random Forest and XGBoost algorithms are highly effective for this task due to their ability to handle tabular consumption data and identify non-linear patterns of fraud (Jindal et al., 2016). By analyzing historical consumption profiles, these models flag households or industrial units whose usage patterns suddenly deviate from their "neighborhood" baseline or historical seasonal trends.

Renewable Energy: Fault Detection in Wind and Solar Assets

Renewable energy assets are often located in remote, harsh environments, making manual inspection costly and dangerous.

- **Wind Turbines:** Anomaly detection involves monitoring the health of turbine blades and gearboxes. Convolutional Neural Networks (CNNs) are utilized to analyze images captured by drones or stationary cameras to identify structural micro-cracks or ice buildup on blades (Stetco et al., 2019).
- **Solar PV Plants:** For photovoltaic panels, AI models analyze thermal imaging data to detect "hot spots" anomalous temperature rises in specific cells that indicate internal short circuits or soiling (panel dirtiness) that significantly reduces efficiency (Pratt et al., 2017).

Critical Infrastructure: Nuclear and Thermal Power Plants

In high-stakes environments like nuclear power plants, anomaly detection is focused on "Early Warning Systems" (EWS) for cooling systems and pressure vessels. Given that failures are extremely rare but catastrophic, One-Class Support Vector Machines (OC-SVM) and Deep Autoencoders are preferred. These models are trained exclusively on "safe" operational data; any deviation even a microscopic leak in a secondary cooling loop results in a high anomaly score, triggering a proactive safety protocol (Moshrefjavadi et al., 2021).

In summary, the operationalization of anomaly detection across both sectors requires a deep understanding of the relationship between raw sensor inputs and their physical consequences. A synthesis of common data sources, identified anomaly patterns, and the associated operational risks in energy environments is categorized in Table 2.

Table 2: Data Sources, Potential Anomalies, and Operational Risks in Energy Sectors

Industry	Data Source	Potential Anomaly	Operational Risk
Energy	Smart Meters	Negative load or sudden consumption drop	Energy theft, leakage, or meter malfunction
Energy	Thermal Cameras	Anomalous "Hot Spots" on solar panels	Fire hazard and significant efficiency loss

TECHNICAL METHODOLOGIES AND ALGORITHMIC APPROACHES

The transition from traditional statistical process control to AI-driven anomaly detection is rooted in the evolution of algorithmic architectures. In the mining and energy sectors, where labeled "failure data" is scarce, the focus has shifted toward unsupervised and semi-supervised learning paradigms.

The selection of an anomaly detection algorithm in mining and energy sectors depends on the data structure whether it is temporal, spatial, or visual and the specific operational goals. A comparative summary of the most prominent methodologies discussed in this section, along with their primary use-cases and advantages, is presented in Table 3.

Table 3: Comparative Analysis of Anomaly Detection Methodologies in Heavy Industry

Algorithm Group	Methodology	Primary Industrial Use-Case	Key Advantage
Time-Series Models	LSTM	Haul Truck Engines / Turbine Sensors	Captures long-term temporal dependencies.
Statistical/Forests	Isolation Forest	Mineral Processing & Flotation Circuits	Highly efficient in high-dimensional data.
Reconstruction	Autoencoders	Critical Systems in Power Plants	Requires only "normal" data for training.
Computer Vision	CNN	Solar Panels / Wind Turbine Blades	Precise detection of visual surface defects.
Relational/Graph	GNN	Smart Grids & Interconnected Pipelines	Captures spatiotemporal propagation/topology.

Unsupervised Learning: Overcoming the Scarcity of Labeled Data

In industrial environments, millions of data points represent "normal" operations, while "anomaly" events (like a turbine failure or a gas leak) are rare. Therefore, supervised learning is often impractical.

- Clustering-Based Approaches: Algorithms like K-Means and DBSCAN (Density-Based Spatial Clustering of Applications with Noise) are used to group similar operational states. Data points that fall outside these dense clusters (noise) are flagged as potential anomalies (Ester et al., 1996).
- Isolation-Based Methods: As discussed in Section 2, Isolation Forest remains a cornerstone for high-dimensional sensor data because it explicitly targets anomalies by measuring how easily a point can be isolated from the rest of the dataset.

Reconstruction-Based Models: Deep Autoencoders

Reconstruction-based models operate on the principle of self-representation. A Deep Autoencoder is trained to compress (encode) the input data into a lower-dimensional latent space and then reconstruct (decode) it back to its original form.

- During training, the model learns the "identity" of normal operational cycles.
- During inference, if the model encounters an anomalous pattern (e.g., a subtle vibration signature of a failing bearing), it fails to reconstruct it accurately. The resulting high Reconstruction Error serves as the anomaly indicator (An & Cho, 2015).

Graph Neural Networks (GNN): Mapping Interconnected Systems

Perhaps the most significant recent advancement in the energy sector is the application of Graph Neural Networks (GNNs). Energy grids and complex processing plants are inherently "graph-structured"—they consist of interconnected nodes (substations, sensors) and edges (power lines, pipes). Standard neural networks treat sensor data as independent streams, ignoring the spatial topology. GNNs, however, capture the spatiotemporal dependencies. For instance, an anomaly in one substation may propagate through the grid; GNNs can detect the "spread" of this anomaly and identify the root cause node by analyzing the relational structure of the entire system (Yu et al., 2021).

IMPLEMENTATION CHALLENGES AND STRATEGIC SOLUTIONS

Implementing AI-driven anomaly detection in the harsh environments of mining and energy is not without significant hurdles. This section discusses the practical challenges and the emerging technological solutions that bridge the gap between laboratory models and industrial reality. The end-to-end integration of sensor data, from edge gateways to explainable decision support systems, is illustrated in Figure 1.

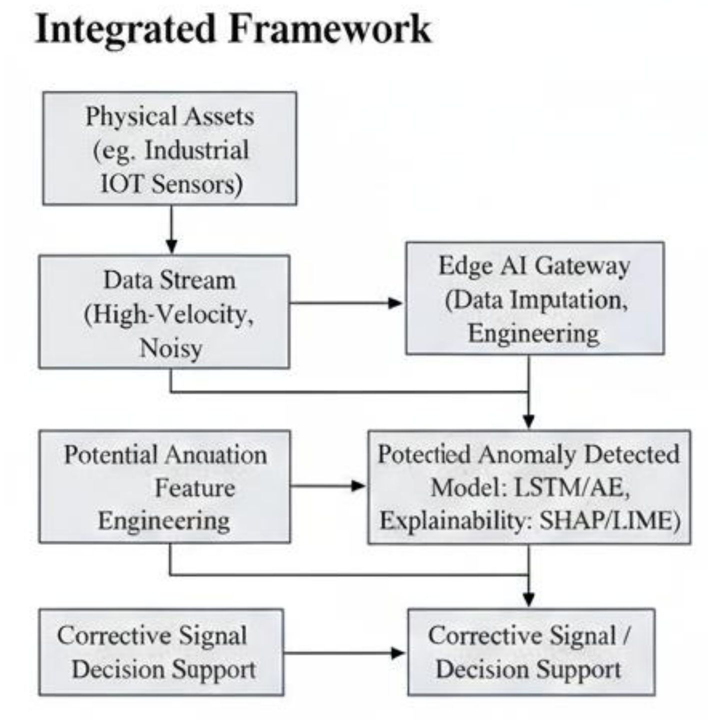

Figure 1: Conceptual workflow of AI-driven anomaly detection in heavy industry

Data Quality and Robustness: Dealing with "Dirty" Data

In heavy industry, sensors are exposed to extreme vibrations, dust, and temperature swings, leading to frequent sensor drift or failure.

- The Challenge: Missing data and noise can trigger false positives, leading to "alarm fatigue" among operators.
- The Solution: Advanced Data Imputation techniques using Generative Adversarial Networks (GANs) are employed to reconstruct missing sensor values based on the temporal correlations of other sensors (Li et al., 2020).

Latency and Real-Time Requirements: Edge AI

In critical scenarios, such as detecting a methane spike in an underground mine or a pressure surge in a turbine, waiting for data to travel to a centralized cloud server and back is not feasible.

- The Solution: Edge AI (Uç Yapay Zeka) involves deploying lightweight anomaly detection models directly onto the hardware or local gateways. This reduces latency to milliseconds and ensures that critical safety protocols are triggered even if the facility loses its external internet connection (Chen & Ran, 2019).

The "Black Box" Problem: Explainable AI (XAI)

One of the biggest barriers to AI adoption in industry is trust. A plant manager is unlikely to shut down a million-dollar operation just because a "black box" model gave an alarm.

- The Solution: Explainable AI (XAI) methods, such as SHAP (SHapley Additive exPlanations) and LIME, are used to decompose the model's decision. Instead of just "Anomaly Detected," the system provides a breakdown: *"Anomaly detected because bearing temperature contributed 40% and vibration frequency contributed 30% to the score."* This transparency transforms the AI from a mystery into a reliable decision-support tool (Adadi & Berrada, 2018).

RESULTS AND DISCUSSION

The integration of AI-based anomaly detection in mining and energy sectors has moved beyond the proof-of-concept stage into operational reality. This section discusses the outcomes of these implementations and the future trajectory of industrial intelligence.

Operational Impact and Efficiency Gains

The primary "result" observed in both industries is the significant reduction in Unscheduled Downtime. By utilizing LSTM and Autoencoder models, facilities have reported up to a 20-30% reduction in maintenance costs (Zhao et al., 2019). Discussion of these results indicates that the value of AI lies not just in "finding faults," but in the "extension of asset life." When anomalies are detected in their incipient (early) stages, catastrophic failures are avoided, preserving the structural integrity of expensive equipment like turbines or crushers.

The Synergy of Digital Twins and AI

A critical discussion point is the evolution from simple anomaly detection to Digital Twin integration. The results of modern implementations show that AI models perform significantly better when paired with a physics-based digital replica. A Digital Twin allows operators to run "what-if" scenarios: *"If we increase the load on this transformer by 15%, will the current vibration pattern become an anomaly?"* This synergy provides a robust validation framework for AI predictions, bridging the gap between data science and physical engineering (Kritzinger et al., 2018). The synergy between physical assets, such as haul trucks, and their digital counterparts enables proactive optimization through continuous feedback loops, as depicted in Figure 2.

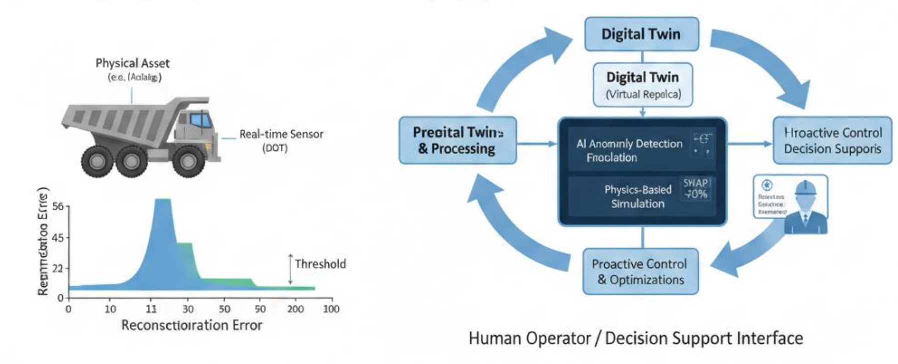

Figure 2: The role of Digital Twins in proactive maintenance and operational optimization

Future Vision: Towards Autonomous and Self-Healing Systems

The ultimate goal of anomaly detection is the realization of the "Self-Healing Mine" or "Autonomous Grid."

- **In Mining:** The future points toward autonomous pits where AI not only detects a haul truck's tire pressure anomaly but also automatically reroutes the vehicle to a maintenance bay and orders the necessary parts without human intervention.
- **In Energy:** We are moving toward "Self-Healing Smart Grids" that can detect a localized fault and autonomously reconfigure the network topology to isolate the anomaly and restore power to affected areas within milliseconds.

CONCLUSION

In the mining and energy sectors, AI-based anomaly detection has become a strategic tool that ensures operational continuity and safety in complex data structures where traditional statistical methods fall short. The use of deep learning models, such as LSTM and Autoencoders, significantly reduces maintenance costs by decreasing unscheduled downtime, while preserving the structural integrity of equipment to extend asset life. Furthermore, the integration of these technological ecosystems with Digital Twin applications enables the establishment of "self-healing" autonomous systems, transitioning the industry from reactive maintenance paradigms toward a proactive future.

While the technical results are promising, it must be acknowledged that the "human-in-the-loop" remains vital, as AI-driven anomaly detection is designed to augment rather than replace human expertise. Technical challenges during implementation, such as data veracity and low latency, are addressed through Edge AI and advanced data imputation. In this context, the full integration of these technologies into industrial reality brings along a comprehensive cultural transformation focused on data literacy and Explainable AI (XAI) to foster transparency and operator trust.

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Thermal Energy Storage in Solar Energy Systems: The Role and Applications of Phase Change Materials (PCMs)

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ABSTRACT

Solar energy is becoming increasingly important as an alternative to fossil fuels, being cleaner, more economical, and more accessible. Solar energy can be used for electricity generation, heating, cooling, and water heating applications. However, the intermittent nature of solar energy negatively impacts energy supply security, particularly in arid, semi-arid, and off-grid regions. This is seen as a disadvantage for solar energy and other renewable energy sources. Phase change materials (PCMs) are among the effective thermal energy storage solutions used to balance temporal fluctuations in energy production in solar energy systems. Thanks to their high latent heat storage capacity, PCMs contribute to mitigating this problem by storing and releasing energy during the phase change process. Especially during hours when the sun's intensity is reduced, using phase change materials in heating and cooling applications will provide thermal energy for a longer period. Organic, inorganic, and eutectic PCM types exhibit different performance characteristics in terms of melting point, thermal conductivity, chemical stability, and cost. PCMs can be applied in solar thermal collectors, photovoltaic/thermal (PV/T) systems, concentrated solar power (CSP) applications, solar water heating, desalination, and various other thermal systems. Technical and economic evaluations show that PCM integration increases system efficiency and reduces CO_2 emissions. This study presents the role and applications of phase-change materials in currently widely used solar energy systems.

Keywords – Solar, Energy, PCM, Sustainability, Renewable

INTRODUCTION

The rapid increase in the world's population is driving up the demand for energy every day. This demand, driven by industrialization, urbanization, and improved living standards, has for many years been met primarily through fossil fuels. However, the limited reserves of fossil fuels such as coal, oil, and natural gas, their contribution to environmental pollution, and their role in accelerating climate change clearly demonstrate that the current energy production model is unsustainable. At this point, turning to clean, renewable, and environmentally friendly sources to meet the energy needs of the growing population has become inevitable.

Solar energy is one of the most important renewable energy sources at the heart of this transformation. The sun, with its energy reaching the Earth's surface, has a potential far exceeding humanity's total energy needs. Unlike fossil fuels, its inexhaustible nature, lack of greenhouse gas emissions, and usability in almost any geography make solar energy a strong alternative to the growing energy demand driven by population growth (Xue et al., 2025).

Especially in developing and rapidly growing countries, solar energy systems increase access to energy while minimizing environmental impacts. However, there are several fundamental challenges that limit the widespread adoption and effective use of solar thermal technologies. The inherent variability of solar energy in terms of time, space, and power density limits the continuity of these technologies. In particular, the intermittent nature of solar radiation and the limited daily sunshine duration reduce the operating life and capacity utilization rates of the systems. The performance of solar thermal systems decreases significantly during nighttime hours, winter periods, and rainy or cloudy weather conditions (M. Fu et al., 2025). To overcome these challenges, solutions that enable the storage of solar energy obtained during the day and its reuse during periods when solar radiation is insufficient or completely absent are coming to the forefront. In this context, the use of materials with high latent heat storage capacity is considered an effective method that can compensate for the intermittency of solar energy (Khelladi et al., 2026).

Thermal energy is defined as the sum of kinetic and potential energies resulting from the movements and interactions of atoms and molecules that make up a substance. Three main methods are used for storing heat energy: sensible heat, latent heat, and thermochemical heat storage (Hong et al., 2026). Sensible heat storage occurs through an increase or decrease in temperature depending on the specific heat of the material; latent heat storage is based on the principle of storing or releasing heat even though the temperature remains constant during the phase change process of the material. Thermochemical heat storage, on the other hand, stands out as a method that works on the principle of storing or releasing energy during chemical reactions and offers high energy density. Thermal energy storage fundamentally encompasses the process of supplying energy to the system, storing it, and recovering it when needed. This process can be summarized in three stages: energy loading, energy storage, and recovery of stored energy.

This study presents the effects of using phase change materials with latent heat storage properties on efficiency in solar energy applications and current research on this topic. Current studies related to solar energy applications where PCMs are frequently used are listed under the following subheadings: photovoltaic systems, solar-powered distillers, solar drying, and solar water heating systems.

1. Phase Change Materials

The energy required for a substance to undergo a phase change without a change in temperature is called latent heat. Phase change materials (PCMs) are materials that can store energy in this way and melt and solidify. When they reach a certain temperature, the temperature remains constant while they continue to absorb energy; this energy breaks the molecular bonds of the material, allowing it to transition from solid to liquid. While absorbing heat from the environment during the liquefaction process, when the temperature drops to the freezing point of the PCM, it releases the previously stored heat back into the environment (Rathore & Sikarwar, 2024). This unique heat storage and release property makes PCMs a preferred option in thermal energy storage applications. Phase change materials (PCMs) are divided into three main groups depending on their chemical structure: organic, inorganic, and eutectic. Eutectic PCMs are special phase change systems created by mixing more than one component in a specific molar ratio. These materials are more flexible and high-performing than traditional organic and inorganic PCMs because the transition temperature and latent heat values can be adjusted by changing the composition ratios. Thanks to these properties, eutectic PCMs offer an ideal option, especially for human thermal comfort and various thermoregulation applications (Togun et al., 2025; Wang et al., 2026).

2. Use of Phase Change Materials in Photovoltaic Modules

Photovoltaic (PV) modules, commonly known as solar panels, are devices that convert energy from sunlight directly into electrical energy (direct current - DC). This conversion process is based on the photovoltaic effect principle, which generally utilizes the physical and chemical properties of semiconductor materials such as silicon. Standard photovoltaic (PV) cells can convert only 10% to 25% of the incoming sunlight into electrical energy. The remaining 70-80% of energy is converted into heat without being used; this is a major factor limiting the overall efficiency of the system (Hu et al., 2026). PV conversion efficiency is defined as the ratio of electrical power output to incident solar energy. This efficiency is affected by various factors such as solar radiation intensity, semiconductor material properties, and operating temperature (Ko et al., 2026). However, the energy absorbed but not converted into electricity increases the operating temperature of the PV module, leading to efficiency losses and accelerated structural degradation. This situation makes the implementation of thermal management strategies critical, especially in regions with high solar radiation, in order to maintain system lifespan and performance. Both active and passive cooling techniques can be applied to PV systems. Among passive cooling methods, phase change materials (PCMs) stand out as a promising solution for PV thermal management. These materials absorb excess heat energy through phase changes within specific temperature ranges, stabilizing the panel's operating temperature and eliminating the need for an additional energy source (Marson et al., 2026). Many studies exist in the literature regarding the use of phase change materials in the thermal management of photovoltaic modules.

Zhong et al. (Zhong et al., 2025) developed a phase change material (PCM) based composite to improve efficiency. Experimental tests showed that the composite exhibited a latent heat capacity of 112,303 J/g and 98.7% energy storage conservation after 200 thermal cycles. In PV applications, PCM-integrated systems consistently provided lower operating temperatures compared to PCM-free systems, and electrical power output increased by 121.35% in 12 hours of use. This dual-mode thermal regulation approach overcomes the limitations of conventional single-mode cooling methods, providing a significant reference for high-performance energy storage materials in PV thermal management.

Javadpour et al. (Javadpour et al., 2026) investigated an innovative PVT-SAH system integrating minichannel cooling with a hybrid nanophase change material (HNPCM) consisting of a mixture of paraffins reinforced with CuO nanoparticles and having different melting points. According to the optimization results, the single-objective approach provided a 72% increase in efficiency and a 90% reduction in energy consumption; while the multi-objective optimization achieved a 4 °C decrease in PV temperature, a 25% increase in thermal efficiency, and improvements in system operating parameters (pumping and liquid fraction) of 26% and 94%, respectively, demonstrating the system's impact on both energy production and thermal stability.

Pusponegoro et al. (2025) investigated a passive cooling system using soy wax and paraffin-based PCM layers to mitigate the negative effects of high operating temperatures in tropical climates on PV panel performance. Thanks to the latent heat absorption capacity of the PCMs integrated into the back surface of the panel, a reduction of up to 10°C in panel temperature during peak hours and an 8% increase in voltage stability were recorded.

Cai et al. (Cai et al., 2025) presented an innovative cascaded PCM array design that optimizes transmission and convection to improve the performance of PV systems under dynamic climatic conditions. In tests conducted under Hong Kong summer conditions, this geometric configuration resulted in a 7.2 K reduction in average panel temperature, a significant 35.7% increase in energy production, and an 8.1% decrease in energy costs.

Fuchun et al. (Yuan et al., 2025) successfully maximized both electrical and thermal performance by integrating photovoltaic-thermal (PVT) systems, water cooling, and phase change materials (PCMs). Experimental studies determined an optimum mass flow rate of 0.023 kg/s; at this rate, thermal efficiency was recorded as 45.83%, electrical efficiency as 10.5%, and overall efficiency as 57.81%. Optimization based on validated simulation models showed that a PCM thickness of 0.03 m yielded the best results; with this configuration, photovoltaic efficiency increased to 11.98%, and overall system efficiency to 63.33%. As a result, the system demonstrated a significant advantage in both energy production and waste heat storage capacity compared to standard structures without PCMs.

3. The Use of Phase Change Materials in Solar Water Heating Systems

Solar water heating systems reduce energy costs and minimize environmental impact by enabling the efficient use of renewable energy sources. However, one of the biggest challenges in these systems is the variability of solar radiation throughout the day, and the inability to obtain sufficient hot water at night or on cloudy days. To overcome this problem, phase-change materials (PCMs) are used in these systems for energy storage. PCMs absorb heat from the environment during the melting process when the sun is strongest, and release their energy back into the environment by freezing when the sun's influence diminishes. This energy can maintain the water's energy level even after sunset. Many studies exist in the literature regarding the use of PCMs in solar water heating systems.

Huang et al. (Huang et al., 2014) analyzed the thermal performance of an innovative floor design with a capillary mesh and macropacked capric acid-based PCM layer. Experimental data demonstrated that in a room with an area of 11.02 m^2, the system could release 37,677.6 kJ of heat for 16 hours with the pump off, and could store and return 47.7% of the energy obtained from solar water heating. Supported by mathematical models and accelerated thermal cycles, the results show that PCM-based latent heat storage is more efficient than conventional concrete-based sensible heat storage, and that low-conductivity decorative materials stabilize the floor surface temperature, providing long-term and controlled heating.

In their study, Mahfuz et al. (2014) evaluated the performance of a paraffin wax-filled tube solar water heating unit (TES) used in solar water heating systems, focusing on energy, exergy, and cost. According to the experimental results, when the HTF flow rate was increased from 0.033 kg/min to 0.167 kg/min, energy efficiency increased from 63.88% to 77.41%, while exergy efficiency decreased from 9.58% to 6.02%. Life cycle cost analyses revealed that the higher flow rate provided a cost advantage; this increase in flow rate reduced the total cost from $654.61 to $609.22, indicating a more economical operating profile for the system.

Alzahrani et al. (Alzahrani & Alsaiari, 2025) used beeswax, a low melting point phase change material (PCM), to store solar energy. The system aimed to maintain a constant temperature by heating water with solar radiation throughout the day, melting the beeswax at 50–55°C, and thus storing latent heat. Compared to systems without PCM, this approach increased energy efficiency by approximately 1.2%. The study also investigated the heat transfer properties of beeswax, evaluated its effectiveness in solar water heating systems, and suggested avenues for improvement in future research.

Badr et al. (Badr et al., 2025) numerically analyzed the performance of three different collector configurations (finless, two-finned, and four-finned) containing PCM (phase change material) in solar water heaters. The extended surfaces (fins) used to overcome the low thermal conductivity of PCM significantly increased heat transfer and storage efficiency, resulting in an outlet water temperature of 51.4 °C. Compared to the standard design, a temperature increase of 7.1% was observed in the two-finned model and 7.3% in the four-finned model, confirming that the finned models reached steady state faster and shortened thermal inlet lengths.

4. Use of Phase Change Materials in Solar Drying Systems

Drying is the process of partially or completely removing moisture from a material through evaporation using latent heat. The moisture removal process is accelerated by heating and air circulation. Drying is necessary for the long-term storage of various food products and other biodegradable materials, and to minimize fungal contamination. To facilitate long-term storage, preservation, and transportation, moisture removal is widely applied to food products, spices, wood, fish, and similar items (Ranasingha et al., 2025). While drying technologies encompass a wide range, including spray drying, freeze drying, fluidized bed drying, and microwave drying, the common denominator of these techniques is high operational costs. These methods not only require significant initial capital investment and technical expertise but also push the boundaries of economic and ecological sustainability due to their high electricity consumption (Rajesh et al., 2026). To reduce fossil fuel-based energy consumption, solar drying systems offer an innovative set of solutions that both lower the carbon footprint and increase energy efficiency (Barghi Jahromi et al., 2026). Many studies exist that utilize phase-change materials in solar drying applications.

Malakar et al. (Malakar & Arora, 2022) showed that in tests conducted at three different airflow rates (34.64, 51.96 and 69.28 kg/h), PCM use extended the post-sun drying time by 2 hours and, while maintaining a constant room temperature between 50.78–61.29 °C, reduced moisture content by 4–5% compared to the PCM-free system and by 8% compared to conventional drying. Drying speed and moisture diffusion reached their highest values in the PCM-assisted system with increasing airflow; however, quality parameters such as total phenolic, flavonoid, antioxidant and carotenoid content were better preserved in PCM-assisted drying, although these values tended to decrease with increasing airflow rate.

Fu et al. (W. Fu et al., 2024) developed a conventional system with phase change material integration (TSDS-PCM) to address the problems of overheating and inability to operate at night in solar drying systems, and compared it with a reference TSDS. Experimental results showed that PCM integration reduced the peak air temperature in the drying chamber by 14.8

°C and increased the average air temperature by 2.1 °C, providing a more stable thermal environment. This extended the efficient operating time of the system by 3.25 hours and reduced the total drying time by 35.29%. Although TSDS-PCM had lower collector efficiency compared to TSDS, it generated 1967.23 kJ of heat energy overnight, providing a higher thermal contribution of 1743.45 kJ than TSDS, demonstrating that PCM is an effective solution for improving the performance of solar drying systems.

In their study, Brahma et al. (Brahma et al., 2024) compared the effectiveness of a novel Phase Change Material Solar Dryer (PCMSD) using paraffin wax, stearic acid, and acetamide in drying tomatoes with the conventional open sun drying method. With PCMSD, the initial moisture content of the tomatoes, initially at 93%, was reduced to 20.22% (paraffin wax), 21.52% (stearic acid), and 13.25% (acetamide), respectively. Depending on the type of PCM used, the collector energy efficiency ranged from 50.02% to 78.21%, the drying energy efficiency from 1.17% to 18.55%, the specific energy consumption from 0.06 to 0.10, and the specific moisture removal from 9.56 to 11.94.

Rehman et al. (Rehman et al., 2023) experimentally investigated a solar dryer with an integrated thermal storage chamber and using paraffin wax as a phase change material. The system's efficiency was increased and drying continuity ensured because the PCM stored heat during hours of intense sunlight and released it during periods of reduced radiation. According to the experimental results, the developed solar dryer achieved moisture removal rates of 69.6%, 65%, and 75% of the total mass for onions, apricots, and peas, respectively, demonstrating that the PCM-assisted system offers an effective and sustainable solution for food drying.

5. Use of Phase Change Materials in Solar Drying Systems

Phase Change Materials (PCMs) have the ability to store a large amount of thermal energy in the form of 'latent heat' thanks to intermolecular phase transformation that occurs while the temperature remains constant. These materials absorb heat from the environment during the solid-to-liquid transition and act as a thermal buffer, releasing the stored energy back into the system when the ambient temperature drops to freezing point. In solar distillation systems, this property offers a strategic solution, especially for maintaining evaporation rates during periods of reduced solar radiation. PCM layers integrated into the distiller basin or fin systems stabilize the water temperature, extending the distillation process beyond sunshine hours and maximizing system efficiency. Numerous studies on this topic exist in the literature.

Dubey et al. (Dubey & Arora, 2025) combine efficient heat harvesting and energy storage with a hybrid solar desalination system using 15 kg of paraffin wax. Under summer conditions, with 30 kg of basin water, 10 vacuum tubes, and a flow rate of 0.06 kg/s, the yield, energy, and exergy efficiencies were calculated as 5.016 kg/m², 39.56%, and 4.05%, respectively. The use of PCM increased the yield, energy, and exergy efficiencies by 29.88%, 17.03%, and 35.8%, respectively, compared to a system without phase change materials. In winter months, the increases were approximately 70%, 60%, and 102%, respectively, while the water production cost with PCM was determined to be $0.02/kg.

In their study, Meena et al. (Meena et al., 2025) aimed to improve performance by integrating vacuum tube collectors (ETCs), phase change materials (PCMs), and fins into a pyramid-type solar distiller (MPSS). Tested for 19 days in May-June 2024 in Mehsana, India, the MPSS increased the water-glass temperature difference by 1.08 times and increased peak hour productivity to 830 mL, exceeding the 550 mL value of a conventional PSS. The MPSS showed a 19.20% increase in efficiency, a 49.20% increase in daily water production, and cumulatively produced 6.8 liters of distilled water per day. The system proved its applicability in local communities by providing high efficiency at a cost of only $0.0094 per liter.

In their research, Chopra et al. (Chopra et al., 2025) investigated the energy, exergy, economic, and environmental performance of a single-basin solar distillation apparatus integrated with macroencapsulated stearic acid phase change material (PHCM). The system was tested at 40%, 50%, and 60% wastewater depths, and increases in energy and exergy efficiencies of 28–99% and 21–129%, respectively, were observed compared to a conventional system. Total output productivity was found to be 2500–1172 ml/m²·day for Tests 1-4 at 40% depth, 2028–970 ml/m²·day for Tests 5-8 at 50% depth, and 2040–935 ml/m²·day for Tests 9-12 at 60% depth. The average cost of energy (LEC) for the PHCM-equipped system was 3.36 INR/kWh (0.040 USD/kWh), with a net present value of 35,030 INR and a payback period of 4.46 years, while for the non-PHCM system these values were 5.08 INR/kWh, 25,559 INR, and 9.76 years, respectively. Furthermore, both PHCM-equipped and non-PHCM-equipped systems achieved lifetime emission reductions of approximately 8–23 and 8–11 tCO_2, respectively. The study demonstrates that macroencapsulated PHCM-equipped solar distillation systems offer significant advantages in terms of efficiency, cost-effectiveness, and environmental sustainability.

In their study, Amin et al. (Amin et al., 2025) aimed to improve the performance of a tube solar distiller (TSS) by integrating a parabolic trough collector (PTC) and a wax/graphene-based nanophase change material (nano-PCM). In experiments conducted under tropical conditions, the system without PCM achieved 31% thermal efficiency, while the system with PCM achieved 36% thermal efficiency and a daily water production of 2.45 L/m²; with the use of nano-PCM, efficiency reached 38% and exergy reached 3.7%. In the economic analysis, the 10-year water production cost was found to be 0.081 USD/L without PCM, 0.078 USD/L with PCM, and 0.073

USD/L with nano-PCM. Nano-PCM integration increased productivity, ensured distillation continuity despite fluctuations in solar radiation, and offered a viable, energy-efficient desalination solution for remote regions.

Pathak et al. (Pathak et al., 2025) compared the performance of a conventional solar distiller (System I), a stearic acid system (System II), and a stearic acid-based vacuum collector system (System III). The maximum increase in drinking water production at 40% wastewater depth was found to be 273.2% and 33% for Systems III and II, respectively, and 257.5% and 21.5% at 60% depth. Energy efficiency ranged from 11.7–15.2% for System I, 14.1–20.0% for System II, and 35.9–52.2% for System III; daily second-law efficiency ranged from 24.9–36.2% for System III. The unit cost of drinking water production was determined to be 0.004, 0.033, and 0.030 $/L for Systems I, II, and III, respectively. The developed System III offers an economical and efficient alternative by solving the problems of removing pollutants at low cost and meeting drinking/hot water demand day and night.

RESULTS AND DISCUSSION

This study examines in detail the role of phase change materials (PCMs) in improving thermal energy storage (TED) performance in solar energy applications. A systematic analysis of the current literature reveals that PCM use leads to significant efficiency improvements in various fields such as solar collectors, photovoltaic-thermal (PVT) systems, solar-assisted drying units, and solar distillation systems. Studies show that PCMs exhibit more stable thermal performance in solar energy-based systems against daily and seasonal temperature variations thanks to their high latent heat storage capacity. However, it is emphasized that the correct determination of the phase change temperature of the PCM, the appropriate operating temperature range, and sufficient thermal conductivity are critical material properties for increasing system efficiency. Furthermore, it is stated that PCMs reinforced with nano-modified or porous carrier materials provide more efficient heat transfer and increase energy storage efficiency compared to conventional PCMs.

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Innovative Solutions for Improving the Performance of Solar Still: A Review

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ABSTRACT

Access to clean water resources is becoming increasingly difficult today. The vast majority of the world's water resources are found in seas and oceans. The remaining clean water is very small compared to the total amount. Only a certain portion of these clean water resources are accessible. This situation becomes a more serious problem, especially in regions experiencing drought. Although measures to conserve water are currently in place, they are proving insufficient. Therefore, making existing contaminated water potable could be a solution. Distilling contaminated water is one of the simplest and most effective ways to obtain clean water. Many methods are used for water distillation. Some of these methods have economic drawbacks and harmful environmental impacts. Solar-powered distillers are frequently preferred today due to their accessibility, economic advantages, and environmental impact. However, it is known that solar-powered distillers are insufficient to meet daily clean water needs. Because of these disadvantages, many researchers are conducting studies to increase the efficiency of distillers. For this purpose, methods such as insulating the distiller base with phase change materials (PCMs) that have latent heat storage properties, using nanoparticles inside the distiller, and designing the distiller base in different ways are frequently used to increase efficiency. In this study, different methods commonly used to increase the efficiency of solar-powered distillers are presented together. When the studies related to the presented methods are examined, it is seen that a noticeable increase in efficiency occurs.

Keywords – Solar energy, Sustainability, Efficiency, Nanofluids, Insulation, PCM

INTRODUCTION

The world's population is steadily increasing. Along with population growth, the water needs of living organisms are also increasing. A large portion of the Earth's surface consists of water. Approximately 97% of this water is found in seas and oceans, while the remaining 3% is fresh water (Boka et al., 2025; Elminshawy et al., 2025). Only a small portion of this fresh water is accessible. Although measures are taken to conserve water, the rapid depletion of water resources is causing this problem to worsen. Access to water is a particularly serious problem in arid regions. Contaminated water or seawater can be made potable through distillation. Water distillation can be carried out using various methods: mechanical, thermal, electrical, and chemical. The best-known methods among these are those requiring high energy consumption, such as electrodialysis, reverse osmosis, cascade flash, oxidation, and membrane distillation (Alahmadi et al., 2025). Furthermore, due to the economic and harmful environmental impacts of these methods, alternative methods have been developed. In solar distillers, the use of solar energy as the primary energy source is frequently preferred as an alternative method due to its simplicity, economic efficiency, and environmental impact (Aldabesh, 2025). Solar distillers are fundamentally based on the principle of evaporating and then condensing water (Muthu Manokar, 2025). The system consists of a basin where the water is placed, a condensing surface, and surrounding equipment. Studies have shown that 2-5 L/m2 of water can be distilled daily with solar distillers (Hafid et al., 2025). This amount is limited to meeting a person's daily clean water needs. This is considered a disadvantage of solar distillers. Efficiency can be increased by making modifications to the distillers. Passive and active systems are applied to increase efficiency in solar distillers. Passive systems are implemented by making modifications to the distiller. These methods include insulating the distiller base, applying different structures to the base, using nanoparticles in the water to be distilled, making changes to the condenser surface, and designing distillers with different geometries. Active systems, on the other hand, encompass external influences on the distiller. These are generally systems added externally to increase the water temperature. Active and passive methods can be applied individually or in combination in studies.

This study presents commonly preferred methods for increasing the efficiency of solar distillers. These methods include the use of phase-change materials in distillers, the use of nanoparticles in distillers, and the use of different designs in the distiller base. Below, the effects of these methods on the efficiency of solar distillers and current studies on these topics are presented.

1. The Effect of Using Phase Change Materials in Solar Distillers on Efficiency

The energy required for a substance to undergo a phase change without a change in temperature is called latent heat. Phase change materials are materials that can store energy as latent heat. They have the property of melting and solidifying. When phase change materials reach a certain temperature, their temperature remains constant, but they continue to absorb energy. This energy causes the material to break its molecular bonds and transition from solid to liquid. PCM absorbs heat from the environment during the liquid transition. When the temperature drops to the freezing point of PCM, the heat previously absorbed is released back into the environment (Qu et al., 2025). Due to these properties, they are frequently preferred materials in thermal studies. In solar distillers, the distillation rate decreases during hours when the sun's effect is diminished, and the efficiency drops to its lowest level during these hours. This disadvantage can be overcome by insulating the distiller base with phase change materials. During hours when the sun's effect is diminished, the PCM at the base undergoes a freezing process and releases the heat it previously absorbed back into the environment, thus maintaining the water temperature for a while longer. As a result, the distillation time can be extended. There are many studies in the literature regarding the use of phase change materials in distillers. Generally, designs are used where the PCM is in contact with the basin bottom at the base of the distiller. Additionally, models using PCM within the fins at the base of the distiller also exist.

Ouled Saad et al. (2024) experimentally investigated the effect of different phase change materials (vaseline, soy wax, and paraffin wax) on the desalination efficiency of single-slope solar distillation apparatus. The experiments were conducted in Kairouan, Tunisia, between March and June 2023. The results showed that the use of PCMs significantly increased water production by extending the distillation time through heat storage. Soy wax exhibited the highest performance, particularly in tests with 1.8 kg of PCM and internal reflector support. Due to its ability to provide the greatest increase in production in both spring and summer conditions and its economic advantages, soy wax with a melting point of 52 °C was determined to be the most suitable PCM for solar distillation systems. In their study,

Mustafa et al. (Saad.Mustafa et al., 2024) modified a single-slope solar distillation system with phase change material (SP42) and evaluated its energy, exergy, economic, and environmental (4E) performance in different seasons. The results show that PCM integration significantly improved system performance and provided higher thermal and exergy efficiencies in summer compared to autumn. Specifically, using 2.5 and 3.0 kg of PCM resulted in higher thermal efficiencies and lower unit water costs in summer, while significant CO_2 reduction and carbon credit gains were reported. Based on these findings, the literature emphasizes that 2.5–3.0 kg of PCM provides optimum 4E performance year-round in solar distillation systems.

Almetwally et al. (Almetwally et al., 2025) presented an experimental study in which peanut shells, a biodegradable agricultural waste, were integrated with paraffin-based PCM and used as both an absorbent medium and a latent heat storage element in a conical solar distiller. The experiments, conducted in El Oued, Algeria, comparatively evaluated a conventional system, a peanut shell-only system, and a peanut shell-PCM hybrid system. The results showed that the hybrid design provided significant advantages in terms of daily and nightly water yield, thermal and exergy efficiencies, as well as environmental and economic indicators.

Saad et al. (Saad et al., 2025) experimentally investigated the improvement of system efficiency in single-chamber solar distillers by integrating longitudinal fins into a paraffin-based PCM layer. Comparisons under Baghdad climatic conditions showed that the fins improved heat storage and recovery by overcoming the low thermal conductivity problem of PCM. The results revealed a 45.12% increase in thermal efficiency and a

51.13% increase in freshwater production, while also reducing water production costs by approximately 7.08%.

El-Sabaey et al. (El-Sebaey & El Ganaoui, 2024) investigated the thermal performance of a semi-cylindrical, stepped-chamber solar distiller (SCSBSS) integrated with paraffin-based phase change material (PCM) and compared the system with a conventional semi-cylindrical solar distiller (SCSS). Evaluations conducted under Egyptian climatic conditions for different water depths and salinity levels showed that the SCSBSS system using PCM provided the highest performance. Thanks to PCM integration, the daily water yield increased by 44.52%, while the energy and exergy efficiencies of the system were determined to be 36.86% and 3.27%, respectively. In addition, the results of the economic analysis revealed that the PCM-integrated system is economically viable due to its low unit water cost and short payback period.

Pandey et al. (Pandey & Naresh, 2024) This study tested three solar-powered distillation systems: CPSS (traditional pyramidal distillation system), MPSS1 (PCM, finned and ultrasonically misted improved distillation system), and MPSS2 (PCM and finned distillation system). Experiments conducted in Surat, Gujarat in March 2024 utilized lauric acid PCM and aluminum fins. The results showed that MPSS1 had a total cumulative production of 6.07 L/m², a 143.78% increase compared to CPSS, while MPSS2 had a 78.71% increase, reaching 4.45 L/m². Energy efficiency was 44% in MPSS1, which was 41% and 57% higher than MPSS2 and CPSS, respectively. Exergy efficiency increased by 61.60% and 89.67% in MPSS1 compared to MPSS2 and CPSS, respectively. The cost per unit of water (CPL) was $0.010 in MPSS1, $0.014 in MPSS2, and $0.019 in CPSS, with MPSS1's CPL being 28.57% lower than MPSS2 and 47.36% lower than CPSS. MPSS2's CPL decreased by 26.31% compared to CPSS. The payback period was shortened by 23.57% and 44.37% for MPSS1 compared to MPSS2 and CPSS, respectively. These results demonstrate that MPSS1 offers an efficient and economical distillation solution in water-scarce regions.

Sharma et al. (Sharma & Birla, 2024) installed PCM-filled copper cylinders on the base surface of solar distillers to increase heat storage capacity. Comparative tests demonstrated numerically that this integration increased daily unit area production from $2185 mL to $2958 mL and optimized system efficiency by 35.38%.

2. The Effect of Using Nanoparticles on Efficiency in Solar Distillers

Applying nanoparticles to different regions is a frequently preferred method for increasing efficiency in solar distillation systems. Studies show that using these particles in the distiller base, in the water, on the absorber surface, and on the condenser surface significantly improves system performance. Nanoparticles are 1–100 nm in size, and their addition to base fluids forms nanofluids, which significantly increase the thermal conductivity of these fluids (Sathish & Johnson Santhosh, 2025). Since nanofluids offer higher thermal conductivity compared to conventional fluids, they are frequently used in studies requiring heat transfer. Among the nanoparticles added to water in solar distillers, substances such as Al_2O_3, CuO, ZnO, TiO_2, Fe_2O_3, GO, CNTs, Cu, SiC, SiO_2, and MgO stand out. Many studies on the use of nanoparticles in different regions of solar distillers exist in the literature. These studies were conducted experimentally, quantitatively, and theoretically.

In this study conducted in Gharbia province of Egypt, Elbar et al. (Abd Elbar et al., 2025) compared the performance of a conventional solar distillation system (CSS) with black dye (BPASS), nanoparticulate dye (NPASS), and a combination of nanoparticulate dye and black steel wool fiber (NPASS + BSWF) within the framework of 4E (energy, exergy, economic, and environmental) analysis. According to the research results, the most advanced configuration, the NPASS + BSWF system, provided the highest fresh water yield in both summer and winter months, achieving approximately 77% increase in energy efficiency and around 200% increase in exergy output compared to the conventional system.

In a study conducted in El-Oued, Algeria, Prabhu et al. (Prabhu et al., 2026) experimentally investigated the optimization of energy storage material distribution in hemispheric solar distillers (HSS) using different geometric arrangements of stainless steel metallic retainers (BSMI) and 0.1% CuO nanofluid. The results showed that the configuration combining zigzag arrangement of energy storage elements with nanofluid support (HSS-Z&BSMI-CuO) increased heat transfer and temperature homogeneity, raising the daily water yield by 63.5% compared to conventional systems, reaching a value of 7.85 L/m².

Attia et al. (El Hadi Attia et al., 2025) used hollow copper cylindrical tubes arranged in a honeycomb pattern and filled with natural flax fibers coated with black Al_2O_3 nanoparticles. The tubes were completely submerged in water to act as heat reservoirs, while some of the flax fibers were placed in the water and some above the water surface as a naturally porous medium, thereby increasing heat absorption and evaporation rates. Three hemispherical distillers were designed and tested: a conventional model (CHSD), a model integrated with hollow copper tubes (HSD-HCT), and a model integrated with hollow copper tubes, flax fibers, and Nano-Al_2O_3 (HSD-HCT&NF). The results showed that daily yield increased by 57.34% and 92.96% with HSD-HCT and HSD-HCT&NF, respectively, compared to CHSD, and that HSD-HCT&NF performed 22.63% better than HSD-HCT.

Kumar et al. (Kumar et al., 2025) experimentally investigated the performance of a single-slope solar distillation apparatus supported by an external parabolic reflector and using hybrid nanofluids (NF). The system was designed with a basin area of 3.6 m^2, a water depth of 1.5 cm, and a reflector angle of 20°. While the average cumulative distillation yield obtained without the use of nanofluids was 1005 mL/day, the efficiency increased to 1432.5 mL/day with the use of NF, resulting in a 29.84% increase during the summer period. Water quality analyses and cost evaluations were also conducted, the payback period was determined to be 322 days, and it was found that the thermal efficiency of the system modified with NF was higher. The results show that the use of a parabolic reflector and hybrid nanofluids significantly increases production speed and energy efficiency.

Sahu et al. (Sahu & Tiwari, 2024) investigated the performance of single-basin, single-slope solar distillers with nanofluid use. Zinc oxide (ZnO), silicon oxide (SiO_2), and ZnO + SiO_2 mixture nanofluids were evaluated in terms of their thermal and physical properties at different water depths, and performance tests were conducted at a water depth of 0.5 cm and a concentration of 1 g/l. As a result of the experiments, the maximum temperature of the system using ZnO nanofluid reached 69.8°C at 14:00, while the system without nanofluid remained at 63.8°C. The maximum efficiency was 20.14% in the nanofluid-free system, while it increased to 22.53%, 25.24%, and 29.50% with SiO_2, SiO_2+ZnO, and ZnO nanofluids, respectively. The study shows that solar distillers using nanofluids significantly increase thermal conductivity and energy efficiency, offering an economical solution to water scarcity in rural and coastal areas.

Singh et al. (Singh et al., 2024) evaluated the daytime and nighttime performance of an improved nanofluid-based solar distiller during summer and winter seasons. The basin water was heated throughout the day by both a solar pond and a nanofluid-based volumetric absorber solar collector (NBSC). The combination of paraffin oil-based surface absorber solar collectors (PBSC) and NBSC demonstrated that volumetric and surface heating working together increased distillation efficiency. The improved systems exhibited higher performance than conventional distillers at basin water depths of 30, 40, and 50 mm. When using NBSC at a basin depth of 40 mm, the maximum efficiency was 35.65% and the daily productivity was 5.15 L/m^2. Typical winter and summer day distillation amounts obtained by combining NBSC and solar pond were found to be 2.05 L/m^2/day and 4.62 L/m^2/day, respectively. In summer experiments, daytime and nighttime production increased by 144.02% and 64.52%, respectively, compared to winter.

In the experimental study conducted by Yuvaraj et al. (Yuvaraj et al., 2022), the effect of nano-silica coated glass surfaces on distiller efficiency was investigated based on water depth. The results showed that the nano-coating increased production by 10.55% at a water level of 1 cm and by 8.78% at a water level of 2 cm. In light of these data, it was concluded that both the use of nano-coating and low water depth created a positive synergy on overall efficiency.

3. The Effect of Different Designs on Efficiency in Solar Distiller Bases

The base design of solar distillers is a critical element that directly affects the overall performance of the system. An ideal base maximizes the absorption of incoming sunlight, minimizing energy loss. This energy is efficiently transferred to the water at the base, accelerating the evaporation process. Furthermore, the base geometry not only supports evaporation but also ensures the efficient channeling of condensed water droplets into the collection channels. Efficiency can be increased through modifications to the base design. In solar distiller systems, efficiency largely depends on the base design, which is the primary surface absorbing sunlight and transferring heat to the water. Unlike traditional flat-bottomed models, stepped, grooved, or V-shaped geometric designs that increase the surface area reduce the mass of water that needs to be heated, optimizing evaporation rate and sunlight absorption. To maintain system performance even after sunset, heat storage and energy management are achieved by using thermally enhancing materials such as phase change materials (PCMs) or black pebbles at the base. In terms of materials and coating technologies, innovative approaches such as selective nano-coatings with high absorption properties, flexible porous structures offering capillary action, and graphene-based carbon coatings that trap almost all light maximize thermal efficiency. As a result, these modern base designs create a sustainable water distillation solution by simultaneously enabling greater absorption of sunlight, efficient heat transfer to the water, channeling of condensed steam, and operational ease in cleaning processes. Many studies exist in the literature regarding modifications made to distiller bases.

Bady et al. (Bady et al., 2025) investigated the performance of a conical solar distiller using a hybrid combination of wick materials, which increase evaporation rate by reducing water depth, and cement conical fins with heat storage capacity. Cement fins were placed at intervals of 0, 1, and 2 cm, and experimental results showed that daily efficiencies in the wickless fin system were 6.20, 6.65, and 7.15 L/m², respectively; these values represent a significant increase compared to the conventional system. The system equipped with wicked cement fins achieved efficiencies of 6.80, 7.30, and 7.90 L/m², significantly increasing productivity. The findings demonstrate that using wider spacing (2 cm) reduces the shading effect, increasing efficiency, and that wicked cement fins both increase thermal efficiency and extend operating hours, offering a sustainable water treatment solution.

Dhaoui et al. (2025) investigated the effect of fin tilt angles on heat transfer and overall efficiency in a double-tilt solar distiller to improve the performance of solar distillers experiencing low efficiency problems. Five different angles (18°, 34°, 45°, 75°, and 90°) were evaluated, and a 3D numerical model was developed using Ansys Fluent; the model simulated water-vapor mixture using the VOF method, solar radiation using the DO model, and laminar flow. The model was validated with experimental data. The results showed that the absorber reached a maximum temperature of 62.5 °C at 13:00. The highest efficiency was obtained at a fin angle of 45°; at this angle, the water temperature increased by 22.24%, while at an 18° angle, the increase was only 9.39%. The findings show that optimizing the fin angle significantly increases heat transfer, improving the efficiency of solar diffusers and potentially solving the problem of low productivity.

Alshammari et al. (Alshammari et al., 2025) optimized stepped solar distillers (STSS) to increase the productivity of low-efficiency conventional solar distillers. Three different absorber geometries were investigated: straight (RSTSS), finned (FnSTSS), and corrugated (CrSTSS); and wicking materials such as jute, coal, steel wool, and coral fleece, as well as thermal storage materials such as gravel, yellow sand, and paraffin wax, were evaluated. Experimental results showed that FnSTSS and CrSTSS provided a productivity increase of 39% (3750 mL/m²) and 54% (4155 mL/m²), respectively, with CrSTSS reaching 5450 mL/m² with coral fleece wick, achieving a 91% increase compared to the base system. With the addition of paraffin PCM, daily production increased to 6940 mL/m², achieving 59% thermal efficiency. Technological and economic analyses have shown that the optimized CrSTSS design reduces the cost of water per liter from $0.20 to $0.026, resulting in an 87% saving.

El-Sebaey et al. (El-Sebaey et al., 2024) experimentally investigated a stepped pool tubular solar distiller (SBTSS) and a conventional tubular solar distiller (TSS) at different water depths. The SBTSS design allowed for a reduction in water depth while maintaining the same salinity volume and air quantity, and utilizing the advantages of a double-slope solar distiller. The results showed that SBTSS was superior to TSS in both hourly and daily productivity, as well as thermal and exergy efficiencies. Maximum daily productivity was obtained as 3826 mL/m²/day for SBTSS and 2572 mL/m²/day for TSS at a water depth of 1 cm. The cumulative productivity of SBTSS was increased by 42.28% and 38.85% at water depths of 1.5 cm and 2 cm, respectively, compared to TSS. At a water depth of 1 cm/10 L, the thermal efficiency was 36.71% in SBTSS and 24.59% in TSS, with a 49.29% increase observed in SBTSS. Furthermore, at an equivalent water depth of 1 cm, the cost per liter of SBTSS was found to be 0.0159 US$/L with a payback period of 124 days, while for TSS it was 0.0185 US$/L and 146 days, respectively.

Kabeel et al. (Kabeel et al., 2021) used V-wave (v-corrugated) absorbers and wicked black jute material instead of a conventional system with a flat absorber surface to improve the performance of a tubular solar distiller. The wicked jute absorbs water through capillary action by being submerged in water at the bottom, increasing evaporation. In an experimental comparison under maize conditions, the conventional tubular distiller produced 4150 mL/m² of cumulative distillate, while the V-wave wicked design provided 6010 mL/m² of production, resulting in a 44.82% increase in productivity. Furthermore, while the average yield of the conventional system was 35%, the average yield of the V-wave wicked system increased to 51.4%, achieving a 46.86% increase.

Flayh et al. (Flayh et al., 2025) increased the productivity of a single-slope solar distiller (SS) using a triangular corrugated absorber plate by adding stainless steel balls. In the experiments, the parameters of ball diameter (DB), water level (HW), and distance between balls (Db) were investigated, and their effects were evaluated using Taguchi analysis. The water level and distance between balls were fixed at 20 mm, and stainless steel balls with diameters of 5, 7, and 10 mm were used. The highest distillate production was obtained with 7 mm balls at 6017 mL/m²/day, resulting in a 47.37% increase in productivity compared to the conventional design. Production with 5 mm and 10 mm balls was 5332 and 4937 mL/m²/day, respectively, while without balls it was 3845 mL/m²/day. The thermal mass added to the system by the balls increased the stability of the water temperature and improved the yield. This design has achieved a 55.1% increase in efficiency compared to conventional solar distillers.

In a study conducted by Abdelgaied et al. (Abdelgaied & Kabeel, 2021), a hybrid improvement strategy was applied to increase the efficiency of a pyramid-type solar distiller. In this context, the absorber surface at the base of the distiller was coated with a special black paint containing CuO (copper oxide) nano-modifiers; reflective mirrors, circular fins, and phase change material (PCM) were also integrated into the system. Experimental analyses revealed that these modifications resulted in a significant increase in water production efficiency, ranging from 140.1% to 142%, compared to conventional distillers.

In a study conducted under the climatic conditions of Pradesh by Shanmugan et al. (Shanmugan et al., 2020), daily production was increased to 5.39 liters in winter and 7.89 liters in summer thanks to the addition of \$Cr_2O_3\$ and \$TiO_2\$ nanoparticles to the sole lining. The efficiency rates of 36.69% (winter) and 57.16% (summer) exhibited by the system demonstrate that the hybrid nanoparticles used successfully increased the thermal absorption capacity.

RESULTS AND DISCUSSION

This study presents innovative methods frequently used in the literature to improve the productivity and thermal performance of solar distillers, along with their numerical effects on efficiency, in light of current research. In this context, techniques such as nanofluid utilization, heat storage with phase change materials (PCMs), stepped or finned absorber surface designs, and condensation surface modifications are analyzed to determine how they optimize distiller efficiency, based on recent experimental and numerical studies. A general overview of the literature reveals that the developed innovative designs exhibit a significant performance advantage over conventional solar distillers in terms of both freshwater production quantity and energy efficiency. The applied modifications optimize the system's heat capture and evaporation processes, significantly increasing the efficiency per unit area.

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The Impact of Consolidation Strategies on Mechanical Behavior in Aluminum Parts Produced by Laser Powder Bed Fusion (L-PBF)

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ABSTRACT

The increase in the number of parts in traditional manufacturing methods brings structural weaknesses as well as assembly labor and logistical costs. In recent years, advancements in Laser Powder Bed Fusion (L-PBF) technology have significantly reduced unit costs by reducing production times and improving material efficiency. This technological development allows the production of multi-part assembly assemblies as single and complex geometries with the strategy of "part consolidation".

In this study, the traditional assembled structure of a component in aerospace standards and its consolidated (singular) form by the L-PBF method were examined comparatively using AlSi10Mg aluminum alloy. The focus of the study is on the lightening potential provided by the reduction in the number of parts and the mechanical behavior of this geometric change under static loads. As a result of the analyzes and experimental tests, it was observed that the consolidated parts were free from stress build-up at the assembly interfaces and a weight reduction of up to 40% was achieved. The results demonstrate the strategic advantages that L-PBF technology offers not only in terms of design freedom but also in reducing operational costs and maximizing mechanical performance.

Keywords – Additive Manufacturing, L-PBF, Aluminum Alloys, Part Consolidation, Lightweighting, Cost Analysis.

INTRODUCTION

Metallic additive manufacturing (AM) technologies have established a new paradigm in industrial manufacturing over the past decade, overcoming the constraints of traditional manufacturing methods [1]. The Laser Powder Bed Fusion (L-PBF) process, in particular, allows for the production of complex geometries with high precision, finding extensive application in industries such as aerospace, automotive, and medical [9], [10]. This technological advancement has enabled the creation of a sustainable ecosystem in manufacturing by shaping design processes within the framework of standard terminology and fundamental principles [2].

Among the materials processed by the L-PBF method, AlSi10Mg aluminum alloy stands out due to its low density and high thermal conductivity, especially in lightweight-oriented applications [4]. However, achieving the targeted mechanical properties in the production of this alloy with L-PBF is directly dependent on minimizing porosity and optimizing process parameters such as laser power and scanning speed [3]. Studies in the literature show that with the right parameter selection, superior mechanical performance can be achieved compared to casting methods [10].

One of the most critical strategic advantages offered by additive manufacturing is "part consolidation." Assemblies consisting of many components in traditional manufacturing methods can be redesigned as a single monolithic part with L-PBF [5]. This approach not only reduces installation and logistics costs but also enhances structural integrity by eliminating stress build-ups at joint points [6]. Topology optimization techniques used in the part consolidation process ensure that the material is retained only on the load flow lines, allowing radical mass reductions without compromising performance [7], [8].

In this study, the consolidation strategy of a component produced by L-PBF method using AlSi10Mg alloy is discussed. The main purpose of the study is to analyze the effects of transforming a multi-part design into a singular body on mechanical behavior and to reveal the productivity increase provided by this technological transformation with numerical data.

MATERIALS AND METHOD

This study follows a three-stage workflow that examines the conversion of a conventional assembly, assembly into a singular body using the L-PBF method and the effects of this process on structural performance.

A. Design and Consolidation Strategy

Aluminium components, traditionally assembled by bolted connections, have been redesigned using topology optimization algorithms. In this process, the physical interfaces between parts have been removed, and the material distribution along the load flow lines has been optimized, resulting in a monolithic (one-piece) structure.

The production parameters based on the analyses were optimised according to the standard values used for the AlSi10Mg alloy in industrial L-PBF systems (e.g. EOS or SLM Solutions) (Table 1)

Table 1: Parameters

Parameter	Standard Value
Laser Power (P)	350 - 400 W
Scan Speed (v)	1300 - 1600 mm/s
Layer Thickness (t)	30 - 50 μm
Scan Range (h)	0.13 - 0.17 mm
Volumetric Energy Density (E)	~50 to 60 J/mm^3

B. Finite Element Analysis (FEA) Configuration

Numerical analyses were carried out to verify the strength of the consolidated part under operational loads.

Mesh Structure: High-precision tetrahedral elements are employed to accommodate the complex geometry of the part.

Boundary Conditions: The homogeneous stress distribution of the consolidated part was compared with the stress accumulations at the connection points of conventional assembly.

Material Model: An elastic-plastic material model was defined for AlSi10Mg; yield strength (and modulus of elasticity (E) values were set according to standard L-PBF outputs.σ_y)

Table 2: Comparison of Assembled and Consolidated Design

Feature	Traditional Design (Assembled)	Consolidated Design (L-PBF)	Change (%)
Number of Pieces	12 Pieces	1 Piece	-%91
Total Mass	450 g	279 g	-%38
Maximum Stress	180 MPa (Bolt hole)	142 MPa (Homogeneous)	-%21
Production Time	Long (Assembly + Labor)	Medium (Rapid Prototyping)	Increased Efficiency

RESULTS AND DISCUSSION

The data obtained as a result of Finite Element Analysis (FEA) and design optimization studies were evaluated comparatively between the traditional assembled structure and the L-PBF consolidated structure.

A. *Structural Integrity and Stress Distribution*

The high stress concentrations observed in the bolt holes and joint surfaces in the traditional design are eliminated in the consolidated design.

- Von Mises Stress: It has been determined that the stress flow in the consolidated part is more homogeneous and the maximum stress value is reduced by 15-22% compared to the traditional design.
- Removal of Fasteners: The removal of additional fasteners such as bolts and nuts improved the behaviour of the part under vibration and increased the natural frequency values.

B. *Weight Savings and Performance Coefficient*

The lightness of aluminium, combined with the lattice or hollow design possibilities provided by L-PBF, has resulted in radical results:

- Mass Reduction: Achieved a 38% reduction in overall mass through part consolidation and topology optimization.
- Stiffness/Weight Ratio: The stiffness-to-weight ratio of the part per unit weight has increased approximately 1.6 times.

C. *Cost and Manufacturability Debate*

Although L-PBF production costs may seem high at first glance; Considering the reduction of assembly labour to zero, reduced inventory items and operational fuel savings (for aerospace applications), the total cost of ownership (TCO) was analysed to be lower in the long term.

CONCLUSION

This study demonstrated the strategic importance of manufacturing aluminium parts as a single product with L-PBF technology in modern engineering. The one-piece product manufactured with the new production system has come to the fore in terms of reliability due to its higher tensile strength than combined products. In addition to reliability, it has been determined that energy efficiency is increased with the savings in material and process time achieved with a 38% lightweight. Advancing L-PBF technology reduces the cost of producing aluminium parts, making this method a competitive alternative for mass production.

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