

Thermal Insulation Systems and Their Impact on Energy Efficiency, Thermal Performance, and Safety of Oil Storage Tanks: A Comprehensive Review

Muheieddin Meftah Elghanudi^{1*}, Zayad M. Sheggaf²

¹Mechanical Engineering Department, Surman College of Science and Technology, Surman, Libya

²Libyan Center for Engineering Research and Information Technology, Bani Walid, Libya

*Corresponding author, e-mail: mganodi2@gmail.com

Abstract

Thermal insulation is an essential component of oil storage tank design and operation, reducing heat transfer between the tank and its surrounding environment while maintaining the desired temperature of stored petroleum products. Effective insulation contributes to improved operational efficiency, reduced energy consumption, enhanced product quality, and lower thermal stresses acting on tank structures, thereby supporting safe and reliable storage operations. This paper presents a comprehensive review of thermal insulation systems used in oil storage tanks. It covers the characteristics of commonly used insulation materials, heat transfer mechanisms, factors affecting insulation performance, insulation thickness optimization, and thermo-economic aspects of insulation design. The review also summarizes recent developments in numerical modeling, particularly Computational Fluid Dynamics (CFD), for evaluating the thermal behavior of oil storage tanks under various operating and environmental conditions, including solar radiation, wind effects, and ambient temperature fluctuations. In addition, the paper reviews the influence of moisture ingress, insulation degradation, and fire exposure on the long-term performance of insulation systems. Emerging developments in smart insulation technologies, real-time condition monitoring, and artificial intelligence applications for insulation performance assessment and maintenance planning are also discussed. Overall, the reviewed literature indicates that selecting appropriate insulation materials and applying well-designed insulation systems can significantly reduce heat losses, improve energy efficiency, and enhance the operational safety of oil storage tanks. The review also highlights several areas that require further investigation, particularly the development of advanced insulation materials, intelligent monitoring techniques, and climate-adaptive insulation solutions for future petroleum storage facilities.

Keywords: Thermal insulation; Oil storage tanks; Heat transfer; Computational Fluid Dynamics; Insulation materials; Energy efficiency.

المخلص

يعد العزل الحراري أحد العناصر الأساسية في تصميم وتشغيل خزانات النفط، إذ يساهم في الحد من انتقال الحرارة بين الخزان والبيئة المحيطة، والمحافظة على درجة حرارة المنتجات النفطية أثناء التخزين. ويساعد استخدام أنظمة العزل المناسبة على تحسين الكفاءة التشغيلية، وخفض استهلاك الطاقة، والحد من التغيرات الحرارية التي قد تؤثر في جودة المنتجات، إلى جانب تقليل الإجهادات الحرارية وتعزيز سلامة الخزانات وموثوقية تشغيلها. تهدف هذه الورقة إلى تقديم مراجعة شاملة لأنظمة العزل الحراري المستخدمة في خزانات النفط، مع تناول خصائص مواد العزل الشائعة والمتقدمة، وآليات انتقال الحرارة، والعوامل المؤثرة في أداء العزل، وطرق تحديد السمك الأمثل، والجوانب الحرارية والاقتصادية المرتبطة بتصميم أنظمة العزل. كما تستعرض الورقة التطورات الحديثة في النمذجة العددية، ولا سيما استخدام ديناميكا الموائع الحسابية (CFD)، لدراسة السلوك الحراري لخزانات النفط في ظل ظروف تشغيل وبيئية مختلفة، بما في ذلك الإشعاع الشمسي، وتأثير الرياح، والتغيرات في درجة الحرارة المحيطة. وتتناول المراجعة كذلك تأثير نفاذ الرطوبة، وتدهور مواد العزل، والتعرض للحريق في الأداء طويل الأمد لأنظمة العزل وفي سلامة الخزانات. كما تستعرض بعض الاتجاهات الحديثة المرتبطة بأنظمة العزل الذكية، والمراقبة اللحظية، وتطبيقات الذكاء الاصطناعي في تقييم أداء العزل ودعم عمليات الصيانة. وتشير الدراسات التي شملتها المراجعة إلى أن اختيار مادة العزل المناسبة وتصميم نظام العزل بما يتلاءم مع ظروف التشغيل والبيئة المحيطة يساهمان بصورة ملحوظة في تقليل الفقد الحراري، وتحسين كفاءة الطاقة، والمحافظة على الاستقرار الحراري، وتعزيز السلامة التشغيلية لخزانات النفط. كما تحدد

المراجعة عددًا من المجالات التي تحتاج إلى مزيد من البحث، ولا سيما تطوير مواد عزل ذات أداء حراري ومثانة أعلى، وتحسين تقنيات المراقبة، وتطوير حلول عزل تتكيف مع الظروف المناخية المختلفة في منشآت تخزين النفط.

Submitted: 01/08/2026

Accepted: 02/09/2026

1. Introduction

In order Oil storage tanks are indispensable components of petroleum production, transportation, and distribution systems. Their primary function is to store crude oil and refined petroleum products while preserving product quality and ensuring a stable supply throughout the production and distribution chain. For this reason, maintaining stable storage conditions has become an important engineering objective in petroleum facilities. In practice, maintaining suitable storage conditions is not only important for operational continuity but also for minimizing energy consumption, reducing maintenance requirements, and ensuring safe handling of petroleum products. Because many petroleum products are temperature-sensitive, even moderate variations in storage temperature may alter viscosity, accelerate product degradation, increase evaporation losses, and complicate downstream processing [1–3].

The thermal behavior of storage tanks is strongly influenced by the surrounding environment. Throughout their service life, tanks are continuously exposed to changing climatic conditions, including solar radiation, daily and seasonal temperature fluctuations, wind, humidity, and, in some regions, harsh desert or coastal environments [4, 5]. These external factors create continuous heat exchange between the tank and its surroundings through conduction, convection, and thermal radiation. Depending on the operating conditions and local climate, heat may either enter or leave the tank, leading to undesirable temperature variations within the stored product. As a result, additional energy is often required to maintain the desired operating temperature, particularly for heavy crude oils and other high-viscosity petroleum products [6].

Among the available engineering solutions, thermal insulation remains one of the most effective approaches for controlling heat transfer in oil storage tanks. By reducing heat flow through the tank walls and roof, insulation systems help maintain more stable storage temperatures while lowering the energy required for heating or temperature control. In addition to improving energy efficiency, properly designed insulation reduces thermal stresses acting on the tank structure, limits excessive temperature gradients, and contributes to safer service conditions [7–9]. Consequently, thermal insulation has become an essential element in modern petroleum storage facilities where energy efficiency, operational reliability, and environmental sustainability are increasingly important.

The effectiveness of an insulation system depends on several interacting factors rather than on the insulation material alone. Material thermal conductivity, insulation thickness, installation quality, environmental exposure, moisture absorption, and long-term ageing all influence thermal performance [10]. Among these materials, mineral wool and polyurethane foam remain the most widely adopted in petroleum storage applications because of their favorable thermal performance and economic feasibility. More recently, advanced materials including silica aerogels, vacuum insulation panels, and nanostructured composites have attracted considerable attention due to their exceptionally low thermal conductivity and potential to achieve superior insulation performance under demanding operating conditions [11].

Despite these technological advances, several practical challenges continue to limit long-term insulation performance. Moisture penetration into porous insulation materials can significantly

increase thermal conductivity, reducing insulation effectiveness and accelerating material deterioration. This issue is particularly critical in coastal regions where high humidity promotes moisture accumulation within insulation layers [12]. Fire resistance is another critical consideration, as insulation systems are expected not only to minimize heat transfer during normal operation but also to delay heat penetration into the tank wall during fire incidents, thereby reducing the likelihood of structural failure and improving emergency response time [13]. These considerations highlight that insulation design should simultaneously address thermal efficiency, durability, reliability, and safety rather than focusing solely on heat-loss reduction.

In parallel with advances in insulation materials, numerical simulation has become an indispensable tool for analysing thermal processes in oil storage tanks. Computational Fluid Dynamics (CFD), together with finite element and transient heat-transfer models, allows researchers to investigate complex thermal phenomena that are difficult to measure experimentally. These approaches provide detailed information on temperature distribution, airflow patterns, heat flux, and thermal gradients under realistic operating conditions involving solar radiation, wind speed, ambient temperature variations, and changing product levels. As computational capabilities continue to improve, simulation techniques are increasingly being integrated with experimental investigations to optimize insulation design and evaluate system performance before field implementation [14,15].

A growing number of studies have investigated individual aspects of thermal insulation in storage systems, including insulation materials, heat transfer mechanisms, numerical modelling, structural behaviour, fire protection, and thermal optimization. Recent review papers have also addressed topics such as CFD applications in thermal energy systems and advanced insulation technologies, reflecting the rapid progress of numerical methods and thermal engineering research [16,18,22]. In addition, machine learning has recently emerged as a promising approach for evaluating insulation integrity and supporting predictive maintenance of storage systems [19]. Nevertheless, these studies generally focus on specific technologies or individual applications, making it difficult to obtain an integrated understanding of thermal insulation performance in conventional petroleum storage tanks. To the best of the authors' knowledge, no recent review has comprehensively integrated conventional insulation materials, advanced insulation technologies, heat transfer mechanisms, thermo-economic optimization, long-term degradation, CFD-based thermal analysis, fire safety considerations, and emerging artificial intelligence applications within a single framework dedicated specifically to oil storage tanks. This limitation makes it difficult for researchers and engineers to identify the most appropriate insulation strategies for different operating and environmental conditions. Addressing this gap is important because modern petroleum storage facilities increasingly require insulation systems that simultaneously achieve high energy efficiency, operational reliability, structural safety, and long-term sustainability.

Accordingly, this review aims to provide a comprehensive overview of thermal insulation systems used in oil storage tanks by integrating current knowledge on insulation materials, heat transfer mechanisms, numerical modelling techniques, thermo-economic analysis, degradation mechanisms, and safety considerations. The review summarizes recent research findings, discusses current engineering approaches, identifies existing knowledge gaps, and outlines future research directions toward the development of more efficient, durable, and climate-adaptive thermal insulation systems for petroleum storage facilities.

2. Fundamentals of Heat Transfer in Oil Storage Tanks

Understanding heat transfer mechanisms in oil storage tanks is essential for designing efficient thermal insulation systems and minimizing energy losses. Heat exchange in storage tanks is governed primarily by the three classical modes of heat transfer: conduction, convection, and radiation, which often occur simultaneously under real operating conditions. In addition, transient thermal effects caused by environmental variations such as day–night temperature changes, wind speed, and solar radiation significantly influence tank thermal behavior over time [16-18].

Figure 1 shows oil storage tank designed to API Standard 650, the core specification for vertical, cylindrical, aboveground steel tanks used across the oil, gas, and petrochemical industries. It sits alongside two companion standards that cover the tank's whole life cycle.

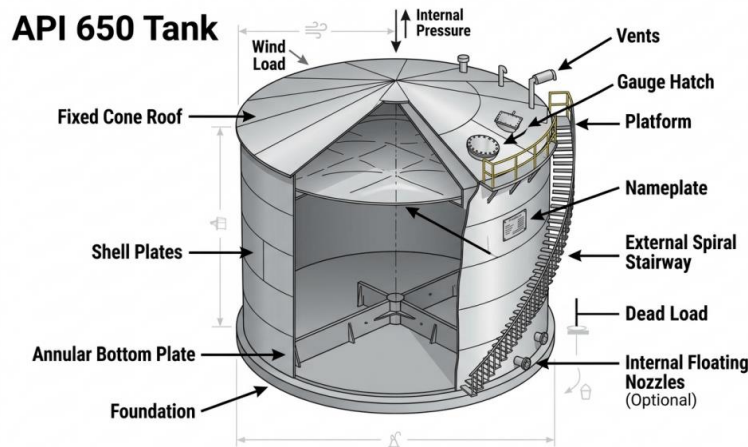


Figure 1. API 650 storage tank

The design establishes minimum requirements for material, design, fabrication, erection, and testing of vertical, cylindrical, aboveground, closed- and open-top, welded carbon or stainless steel tanks for internal pressures approximating atmospheric pressure, and applies only to tanks whose entire bottom is uniformly supported, in non-refrigerated service up to about 93°C (200°F). It's meant to serve as a purchase specification, so the purchaser is expected to spell out certain basic requirements when ordering a tank to this standard [19].

2.1 Conduction Heat Transfer

Conduction is the transfer of heat through solid materials due to temperature gradients and represents the primary mechanism of heat flow through the tank wall and insulation layers [16]. In oil storage tanks, conductive heat transfer occurs from the stored fluid through the steel wall and subsequently through the insulation material toward the external environment. The rate of conductive heat transfer depends on the thermal conductivity of the materials, insulation thickness, and temperature difference across the wall [20]. Therefore, selecting insulation materials with low thermal conductivity is essential for reducing heat loss and improving thermal efficiency. Fourier's law describes one-dimensional steady-state conductive heat transfer:

$$q = -kA \frac{dT}{dx}$$

Where q is the heat transfer rate, k is the thermal conductivity, A is the heat transfer area, and (dT/dx) is the temperature gradient [16].

2.2 Convective Heat Transfer

Convection occurs between the tank surface and the surrounding fluid, typically air, and can be classified as natural or forced convection [17]. Natural convection results from buoyancy forces generated by temperature differences, whereas forced convection is mainly caused by wind movement around the tank surface [21]. For outdoor oil storage tanks, wind-induced forced convection can significantly increase external heat loss, particularly at exposed roof and wall surfaces [18]. In addition, natural convection develops within the stored oil, especially in large tanks, leading to temperature stratification and non-uniform thermal fields [22]. These phenomena strongly influence the thermal performance of storage tanks and the effectiveness of insulation systems. Convective heat transfer is commonly expressed using Newton's law of cooling:

$$q = h A_s (T_s - T_\infty)$$

Where q is the convective heat transfer rate, h is the convective heat transfer coefficient, A is the surface area exposed to the fluid, T_s is the surface temperature, and T_∞ is the ambient fluid temperature [17].

2.3 Radiative Heat Transfer

Radiative heat transfer plays an important role in the thermal behavior of oil storage tanks exposed to outdoor environments. During daytime operation, solar radiation can significantly increase the external surface temperature of tank walls and roofs, particularly in hot and arid regions [18, 23]. This additional thermal load contributes to temperature fluctuations within the stored product and may increase evaporation losses and energy consumption. During nighttime periods, tanks lose heat through long-wave thermal radiation to the surrounding atmosphere. The magnitude of radiative heat transfer depends on factors such as surface emissivity, external cladding characteristics, and environmental conditions [23]. Consequently, surface coatings and insulation jacketing materials can have a noticeable impact on the overall thermal performance of storage tanks.

The Stefan-Boltzmann equation calculates the rate of thermal radiation energy emitted by an object. For a real object, the formula is:

$$P = \epsilon \sigma A T^4$$

Where, (P) is power in Watts, ϵ is emissivity ($0 < \epsilon \leq 1$), (σ) is the Stefan-Boltzmann constant ($\approx 5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$), A is surface area, and (T) is temperature in Kelvin [16].

2.4 Transient and Steady-State Thermal Analysis

Thermal analyses of oil storage tanks are generally classified as either steady-state or transient. Steady-state analysis assumes constant boundary conditions and thermal equilibrium over time, whereas transient analysis accounts for time-dependent variations in environmental and operational conditions [16]. In practice, storage tanks are continuously subjected to changing ambient temperatures, solar radiation intensity, and wind conditions. Therefore, transient thermal analysis provides a more realistic representation of actual tank behavior [18]. Recent numerical studies have demonstrated that transient simulations can accurately predict temperature distributions, thermal gradients, and heat-loss rates that cannot be captured adequately using steady-state approaches, as shown in Table 1 [22, 24]. As a result, transient modeling has become an important tool for evaluating insulation performance, optimizing insulation thickness, and improving the thermal management of oil storage tanks under realistic operating conditions.

Table 1: Summary of Previous Studies on Heat Transfer and Thermal Behavior of Oil Storage Tanks

Ref.	Author(s)	Year	Method	Main Contribution
[18]	Sun et al.	2023	CFD	Investigated transient cooling behaviour under dynamic climatic conditions
[24]	Liu et al.	2018	Numerical Modelling	Evaluated temperature distribution in floating-roof oil tanks
[38]	Sun et al.	2023	CFD	Analyzed environmental factors affecting tank cooling
[39]	Zhang et al.	2025	VOF-CFD	Investigated multiphase heat transfer during crude oil cooling

3. Types of Thermal Insulation Materials

Thermal insulation materials play a crucial role in reducing heat losses, maintaining product temperature, and improving the overall energy efficiency of oil storage tanks. The selection of an appropriate insulation material depends on several factors, including thermal conductivity, moisture resistance, fire performance, mechanical durability, and economic considerations. Over the years, both conventional and advanced insulation materials have been developed to meet the increasing demand for energy-efficient industrial storage systems [25, 26].

3.1 Conventional Insulation Materials

Conventional insulation materials remain the most widely used in oil storage tank applications because of their availability, relatively low cost, and established industrial performance. Among these materials, mineral wool, glass wool, and polyurethane foam are the most commonly applied. Mineral wool is widely used in industrial insulation systems due to its low thermal conductivity, excellent fire resistance, and dimensional stability at elevated temperatures. These characteristics make it suitable for petroleum storage facilities operating under varying environmental conditions [26]. Glass wool is another commonly used insulation material characterized by low density and good thermal resistance. However, its thermal performance may deteriorate when exposed to moisture for extended periods, making proper protection against water ingress essential. Polyurethane foam (PUF) is considered one of the most effective conventional insulation materials because of its low thermal conductivity and high thermal resistance. Consequently, it is frequently used in heated storage tanks and industrial facilities where temperature control is critical. Polyurethane foam generally exhibits better moisture resistance than many fibrous insulation materials due to its closed-cell structure [27].

3.2 Advanced Insulation Materials

Growing concerns regarding energy conservation and environmental sustainability have encouraged the development of advanced insulation materials with superior thermal performance. Among the most promising technologies are aerogel-based insulation materials and high-performance composite insulation systems. Aerogels possess an extremely porous nano-structure that significantly suppresses heat transfer through conduction and convection. As a result, aerogel-based materials exhibit thermal conductivities considerably lower than those of conventional insulation materials while maintaining lightweight characteristics [29]. Recent developments in advanced insulation systems have also focused on reducing insulation thickness while maintaining equivalent thermal resistance. Such materials offer significant potential for industrial applications where space limitations and thermal efficiency are simultaneously important considerations. Despite their superior thermal performance, advanced insulation materials remain limited in large-

scale industrial applications because of their relatively high cost and installation requirements. Nevertheless, ongoing developments in material engineering are expected to improve their economic feasibility in future petroleum storage systems [30].

3.3 Effect of Moisture on Insulation Performance

Moisture accumulation is one of the most important factors affecting the long-term performance of thermal insulation systems. The presence of moisture within porous insulation materials increases effective thermal conductivity and reduces insulation efficiency. Experimental studies have demonstrated that even moderate moisture absorption can significantly alter the thermal properties of insulation materials, leading to increased heat losses and reduced energy efficiency. Furthermore, prolonged exposure to humid environments may accelerate material degradation and shorten insulation service life. For oil storage tanks located in coastal regions or areas with high humidity, moisture resistance should therefore be considered a primary criterion when selecting insulation materials [28].

3.4 Fire Safety Considerations

Thermal performance and insulation materials play an important role in enhancing the safety of oil storage tanks. During fire exposure, insulation systems act as thermal barriers that delay heat penetration into the tank wall and reduce the rate of temperature increase within the stored product. Numerical studies have shown that increasing insulation thickness can significantly improve fire resistance by extending the available emergency response time and reducing structural damage caused by excessive temperatures [31]. Consequently, fire performance should be incorporated into insulation material selection and design procedures, particularly in petroleum storage facilities where fire hazards are a major concern.

3.5 Selection Criteria for Oil Storage Tank Insulation

The selection of insulation materials for oil storage tanks requires balancing thermal performance, safety requirements, durability, and economic considerations. Materials with low thermal conductivity generally provide superior energy savings; however, factors such as moisture resistance, fire protection capability, installation cost, and lifecycle performance must also be evaluated. Modern insulation design increasingly incorporates thermo-economic analysis to identify insulation configurations that minimize total lifecycle cost while maintaining acceptable thermal performance. Table 2 shows common insulation materials used in oil storage tanks [32]. Therefore, the optimal insulation solution depends on operating temperature, environmental conditions, safety requirements, and project-specific economic constraints.

Table 2. General Characteristics of Common Insulation Materials Used in Oil Storage Tanks (based on Refs. [26–32]).

Material	Thermal Conductivity (W/m·K)	Moisture Resistance	Fire Resistance	Relative Cost	Typical Application
Mineral Wool	0.035–0.045	Moderate	Excellent	Low	Above-ground oil storage tanks, industrial equipment, high-temperature applications
Glass Wool	0.032–0.045	Moderate	Good	Low	General industrial insulation, storage tank walls and roofs

Polyurethane Foam	0.020–0.028	Good	Moderate	Medium	Heated oil storage tanks, temperature-controlled storage systems
Aerogel Composite	0.013–0.018	Excellent	Excellent	High	High-performance insulation systems, space-constrained applications
Vacuum Insulation Panels (VIPs)	0.004–0.008	Excellent	Good	Very High	Specialized high-efficiency thermal insulation applications

Note: Thermal conductivity values represent typical ranges reported in the literature and may vary depending on material composition, density, temperature, and moisture content. Actual performance should be evaluated according to operating conditions and manufacturer specifications.

Although insulation material properties strongly influence thermal performance, the effectiveness of an insulation system also depends on insulation thickness. Even high-performance materials may provide limited energy savings if the thickness is insufficient. Consequently, determining the optimum insulation thickness has become one of the most important research topics in industrial thermal management and oil storage applications.

4. Thermal Insulation Thickness Optimization and Thermo-Economic Analysis

Thermal performance of an insulation system depends not only on the properties of the insulation material but also on its thickness. While increasing insulation thickness generally reduces heat transfer and energy losses, excessive thickness may result in unnecessarily high installation costs. Therefore, determining the optimum insulation thickness is a key engineering challenge that requires balancing thermal efficiency and economic feasibility [26, 32].

4.1 Concept of Optimum Insulation Thickness

Optimum insulation thickness is defined as the insulation thickness that minimizes the total lifecycle cost of a thermal system. The total cost generally consists of two main components: the insulation investment cost and the energy cost associated with heat losses during operation [32, 33]. When insulation thickness increases, heat loss decreases and energy savings improve. However, the cost of insulation materials and installation simultaneously increases. Consequently, an economic optimum exists where the combined cost reaches a minimum value.

Numerous studies have demonstrated that selecting insulation thickness based solely on thermal considerations may lead to economically inefficient designs. Therefore, thermo-economic optimization methods have become standard tools in industrial insulation design [26].

4.2 Thermo-Economic Evaluation Methods

Thermo-economic analysis combines heat transfer calculations with economic assessment to evaluate insulation performance over the service life of a system. Typical economic parameters include energy price, inflation rate, interest rate, insulation cost, maintenance expenses, and operational lifetime [32, 34]. One of the most widely used approaches is the lifecycle cost analysis (LCCA), which evaluates the total cost of ownership throughout the operational period of the insulated system. This method allows engineers to quantify long-term energy savings and determine the economic viability of different insulation configurations [34]. Recent studies have

emphasized that energy price is one of the most influential variables affecting optimum insulation thickness. Higher energy costs generally justify thicker insulation layers due to the increased economic value of energy savings [35].

4.3 Applications in Oil Storage Tanks

The optimization of insulation thickness is particularly important for oil storage tanks because of their large surface area and continuous exposure to environmental conditions. Inadequate insulation may result in substantial heat losses, increased product temperature fluctuations, and higher operational costs [6, 18]. Numerous thermo-economic studies have demonstrated that optimum insulation thickness depends on operating conditions, energy prices, climatic factors, and lifecycle cost considerations. For spherical storage tanks, numerical studies demonstrated that increasing insulation thickness significantly reduces heat losses during the initial stages, while the economic benefit gradually diminishes beyond a certain thickness [35]. Similarly, studies on industrial thermal systems and pipelines reported that insulation thickness optimization can produce substantial energy savings while reducing greenhouse gas emissions and operational expenditures [24, 25].

4.4 Influence of Climatic Conditions

Environmental conditions strongly influence the optimum insulation thickness of oil storage tanks. Ambient temperature, solar radiation, wind speed, and humidity directly affect heat transfer rates and insulation performance [18, 22]. In hot climates, insulation primarily reduces heat gain from the environment, whereas in cold climates it minimizes heat loss from the stored product. Consequently, identical insulation materials may require different optimum thicknesses depending on geographical location and operating conditions [35]. Recent simulation studies have demonstrated that climatic factors should be incorporated into thermo-economic optimization models to achieve realistic and reliable insulation designs [34, 35].

4.5 Future Trends in Insulation Optimization

Recent advances in computational modeling and digital technologies have introduced new approaches for insulation optimization. Numerical methods based on Computational Fluid Dynamics (CFD) enable detailed analysis of heat transfer processes under realistic operating conditions [18, 23]. Furthermore, emerging technologies such as machine learning, digital twins, and artificial intelligence are increasingly being investigated for predicting thermal behavior and identifying optimal insulation configurations with reduced computational effort [36]. These developments are expected to improve insulation system design, enhance energy efficiency, and support sustainable operation of petroleum storage facilities in the future.

4.6 Summary

The determination of optimum insulation thickness represents a critical aspect of thermal management in oil storage tanks. Effective insulation design requires the integration of heat transfer analysis with economic evaluation to balance energy savings and investment costs. Existing studies consistently demonstrate that thermo-economic optimization can significantly improve energy efficiency, reduce operational expenses, and enhance the long-term sustainability of petroleum storage systems.

Table 4: Summary of Studies on Optimum Insulation Thickness and Thermo-Economic Analysis

Ref.	Author(s)	Focus	Main Finding
[31]	Kaynakli	Economic insulation	Optimum thickness minimizes lifecycle cost
[32]	Dombaycı	Industrial insulation	Energy price strongly affects optimum thickness
[33]	Hasan	Pipeline insulation	Economic analysis is essential for insulation design
[34]	Alrasheed	Multilayer insulation	Layer configuration affects optimum thickness
[35]	Dolgun et al.	Spherical tanks	Tank size influences optimum thickness

5. Thermal Performance of Insulated Oil Storage Tanks

The primary objective of thermal insulation in oil storage tanks is to reduce heat transfer between the stored product and the surrounding environment. Effective insulation systems contribute to maintaining product temperature, reducing energy consumption, minimizing thermal losses, and improving operational efficiency. The thermal performance of insulated storage tanks depends on several interacting factors, including insulation material properties, insulation thickness, tank geometry, environmental conditions, and operating temperature [18, 31].

5.1 Reduction of Heat Losses and Temperature Fluctuations

One of the most significant benefits of thermal insulation is the reduction of heat losses from stored petroleum products. Heat transfer through tank walls and roofs can result in substantial temperature decreases, particularly in heated storage systems and regions with large day–night temperature variations [18]. Several numerical and experimental investigations have demonstrated that properly designed insulation systems significantly reduce heat flux through tank boundaries, thereby maintaining a more stable internal temperature distribution. Reduced temperature fluctuations are particularly important for heavy crude oils and petroleum products whose viscosity is highly sensitive to temperature variations [18, 23]. Recent investigations under dynamic environmental conditions demonstrated that ambient temperature, solar radiation, wind speed, crude oil viscosity, density, and specific heat capacity significantly influence the cooling behaviour of stored crude oil. The results showed that external environmental conditions dominate heat losses near the tank roof and wall regions, whereas crude oil properties exert greater influence within the bulk liquid region [37]. Furthermore, insulation decreases the rate of thermal energy exchange with the environment, enabling longer storage periods while maintaining product quality and reducing reheating requirements [24].

5.2 Temperature Distribution within Storage Tanks

Temperature distribution inside oil storage tanks is rarely uniform. Variations in ambient conditions, solar radiation, and heat losses through tank surfaces create thermal gradients within the stored liquid [23]. Computational Fluid Dynamics (CFD) studies have shown that insulation significantly influences the magnitude of these temperature gradients. By reducing external heat transfer, insulation promotes more stable thermal conditions and limits excessive temperature differences between the upper and lower regions of the tank [18]. In insulated tanks, the thermal stratification phenomenon may still occur, particularly in large-capacity storage tanks. However, insulation helps reduce the intensity of stratification by limiting heat losses through the tank shell and roof [23]. Advanced numerical simulations of waxy crude oil storage tanks have further revealed that low-temperature zones tend to develop near tank boundaries and phase interfaces

during cooling processes. These findings confirm the importance of thermal insulation in mitigating temperature gradients and maintaining thermal stability throughout the storage period [38].

5.3 Influence of Environmental Conditions

The effectiveness of thermal insulation is strongly influenced by environmental conditions. Ambient temperature, wind speed, humidity, and solar radiation all affect heat transfer rates between the tank and its surroundings [18, 22]. Wind is particularly important because it increases external convective heat transfer coefficients and accelerates heat losses from exposed tank surfaces. Numerical simulations under realistic climatic conditions have demonstrated that wind-induced convection can significantly increase heat losses, especially from the upper sections of storage tanks [18]. Solar radiation and wind-induced convection have been identified as dominant external factors affecting tank thermal performance. Recent three-dimensional heat transfer models showed that wind speed significantly increases heat losses from exposed tank surfaces, while solar radiation contributes to complex transient temperature distributions throughout the storage cycle. Consequently, environmental conditions must be explicitly considered when evaluating insulation performance and designing thermal protection systems for oil storage tanks [37].

5.4 Impact on Energy Efficiency and Operational Costs

Improved thermal performance directly contributes to enhanced energy efficiency in petroleum storage facilities. By reducing heat losses, insulation lowers the energy required for product heating, temperature maintenance, and viscosity control [24, 31]. Several thermo-economic studies have reported that effective insulation systems can substantially decrease operational energy consumption while simultaneously reducing fuel usage and associated greenhouse gas emissions [25, 31]. The resulting reduction in operating costs often justifies the initial investment in insulation materials, particularly for tanks operating continuously over long service periods. Consequently, thermal insulation is widely recognized as one of the most cost-effective energy conservation measures available for industrial storage systems [25].

5.5 Thermal Performance Assessment Using Numerical Simulation

Modern research increasingly relies on numerical simulation techniques to evaluate the thermal performance of insulated oil storage tanks. CFD models allow detailed investigation of heat transfer mechanisms, temperature fields, and insulation effectiveness under realistic operating conditions [18, 23]. These simulation approaches enable engineers to examine the effects of insulation thickness, material properties, climatic conditions, and tank geometry without the cost and complexity associated with full-scale experimental testing. As a result, numerical modeling has become an essential tool for optimizing insulation design and predicting long-term thermal behavior in petroleum storage applications [23]. Recent developments in CFD modelling have enabled detailed simulation of multiphase heat transfer processes within oil storage tanks. For example, Volume of Fluid (VOF) models have been successfully applied to investigate thermal evolution in tanks containing crude oil, gas, and bottom water layers. Such approaches provide valuable insights into transient cooling mechanisms and support the development of more efficient insulation strategies [38]. Recent advances in computational methods have further improved the accuracy of thermal performance predictions, facilitating more reliable design and operational decision-making processes.

5.6 Summary

The thermal performance of insulated oil storage tanks is governed by the interaction between insulation properties, environmental conditions, and operational parameters. Effective insulation systems reduce heat losses, stabilize product temperature, improve energy efficiency, and lower operating costs. Numerical and experimental studies consistently demonstrate that proper insulation design significantly enhances storage performance while supporting safe and sustainable petroleum operations. Therefore, evaluating thermal performance remains a critical component in the design and optimization of modern oil storage tank systems.

6. Numerical Modeling and CFD Applications in Oil Storage Tank Insulation

Numerical modeling has become an essential tool for investigating heat transfer phenomena in oil storage tanks and evaluating the effectiveness of thermal insulation systems. Experimental studies on large-scale storage tanks are often expensive, time-consuming, and difficult to perform under controlled operating conditions. Consequently, numerical approaches, particularly Computational Fluid Dynamics (CFD), have been widely adopted to analyze temperature distribution, heat losses, fluid flow, and thermal stratification within storage tanks [23, 37].

6.1 Role of CFD in Thermal Analysis of Oil Storage Tanks

Computational Fluid Dynamics (CFD) provides a detailed description of heat transfer mechanisms occurring inside and around storage tanks by simultaneously solving the governing equations of mass, momentum, and energy conservation [39, 40]. Unlike simplified analytical methods, CFD models can account for complex geometries, transient environmental conditions, and coupled heat transfer processes involving conduction, convection, and radiation. In oil storage applications, CFD simulations enable the prediction of temperature evolution within the stored product, assessment of insulation effectiveness, and evaluation of environmental influences such as solar radiation, wind-induced convection, and transient climatic variations. Recent three-dimensional numerical studies demonstrated that CFD models can successfully capture the coupled effects of external environmental conditions and crude oil thermophysical properties on storage tank cooling behavior [37]. As a result, CFD has become an indispensable design and optimization tool for thermal management systems in petroleum storage facilities.

6.2 Governing Physical Processes

The thermal behavior of insulated storage tanks is governed by several interacting physical mechanisms. Heat conduction occurs through the tank wall and insulation layer, while natural and forced convection influence heat transfer within the stored liquid and surrounding air. In addition, thermal radiation from solar exposure and surrounding surfaces may contribute significantly to the overall heat balance [22, 39]. Numerical models typically solve the transient energy equation together with the Navier–Stokes equations to capture fluid motion and temperature variations within the storage tank. Advanced models may also incorporate multiphase flow, phase change phenomena, and temperature-dependent thermophysical properties to improve prediction accuracy [38]. Recent CFD investigations have shown that the simultaneous consideration of forced convection, natural convection, thermal radiation, and transient environmental conditions significantly improves the prediction of temperature evolution in large crude oil storage tanks [37]. Such comprehensive approaches provide more realistic simulations of actual operating environments.

6.3 Modeling of Thermal Stratification

Thermal stratification is one of the most important phenomena observed in large oil storage tanks. It occurs when temperature differences develop between fluid layers due to uneven heating or cooling processes. Excessive stratification can affect product quality, viscosity distribution, and operational efficiency [23]. CFD simulations have demonstrated that insulation systems significantly influence stratification behavior by reducing external heat losses and limiting temperature gradients across the stored liquid volume. Numerical studies further indicate that insulation thickness, tank geometry, and environmental conditions play important roles in determining the magnitude and persistence of thermal stratification [37]. Recent multiphase simulations based on the Volume of Fluid (VOF) approach have provided detailed insights into temperature evolution near oil–gas and oil–water interfaces, revealing complex transient thermal behavior during long-term storage operations [38]. The simulations demonstrated that low-temperature regions progressively develop near tank boundaries and phase interfaces, emphasizing the importance of insulation systems in controlling thermal gradients and reducing energy losses.

6.4 Evaluation of Insulation Performance Using CFD

One of the major advantages of CFD is its ability to evaluate insulation performance under realistic operating conditions. Numerical models can simulate different insulation materials, thicknesses, and environmental scenarios without requiring costly full-scale experiments [39]. Researchers have employed CFD to quantify heat losses through tank walls and roofs, identify critical regions of thermal leakage, and optimize insulation configurations for improved energy efficiency [18]. Numerical studies further indicate that CFD can identify critical heat-loss regions around tank walls, roofs, and bottom sections, enabling more effective insulation design and thermal management strategies [37]. These studies consistently demonstrate that properly designed insulation systems reduce temperature fluctuations, decrease energy consumption, and improve thermal stability within storage tanks. Furthermore, CFD-based optimization approaches enable the comparison of alternative insulation strategies and support thermo-economic decision-making processes discussed in the previous section [31].

6.5 Recent Advances in Numerical Modeling

Recent advances in CFD modeling have enabled the simulation of highly complex multiphase heat transfer processes in oil storage tanks. Advanced techniques such as the Volume of Fluid (VOF) method allow accurate tracking of oil–gas and oil–water interfaces while simultaneously solving transient heat transfer phenomena. These capabilities significantly improve the prediction of cooling behavior and thermal stratification in crude oil storage systems [38]. High-resolution computational meshes, advanced turbulence models, and improved radiation models have further enhanced simulation accuracy under realistic environmental conditions [40]. Consequently, modern CFD tools are capable of providing detailed thermal information that was previously difficult to obtain through experimental measurements alone. In addition, the integration of CFD with optimization algorithms and artificial intelligence techniques has opened new opportunities for insulation system design. Machine learning-assisted models can reduce computational time while maintaining acceptable prediction accuracy, making them attractive tools for industrial applications. Digital twin technology is also emerging as a promising approach for real-time monitoring and predictive analysis of storage tank thermal performance. By continuously integrating sensor data with numerical simulations, digital twins can support proactive maintenance strategies and improve operational efficiency [36].

6.6 Challenges and Future Research Directions

Despite substantial progress, several challenges remain in the numerical modeling of insulated oil storage tanks. Accurate representation of environmental boundary conditions, material aging effects, moisture accumulation within insulation systems and long-term operational variability continues to present difficulties for researchers [27]. Future research should focus on developing coupled thermo-hygro-mechanical models capable of simultaneously considering heat transfer, moisture transport, and structural behavior. Such integrated approaches would provide a more comprehensive understanding of insulation performance under realistic operating conditions. Moreover, increased availability of field monitoring data and advanced sensing technologies is expected to improve model validation and enhance confidence in numerical predictions. The integration of CFD, optimization techniques, and data-driven methods will likely play a central role in the next generation of thermal management systems for petroleum storage facilities.

6.7 Summary

Numerical modeling and CFD techniques have become indispensable tools for evaluating thermal performance and insulation effectiveness in oil storage tanks. By providing detailed insights into heat transfer mechanisms, thermal stratification, and environmental interactions, CFD enables more accurate design and optimization of insulation systems. Recent advances in multiphase modeling, artificial intelligence, and digital twin technologies offer promising opportunities for improving thermal management, reducing energy consumption, and enhancing the operational reliability of petroleum storage facilities.

Table 5: Summary of CFD Applications in Oil Storage Tank Thermal Analysis

Ref.	Numerical Method	Application
[24]	CFD	Temperature field prediction
[38]	CFD	Environmental effects on cooling
[39]	VOF-CFD	Multiphase heat transfer
[40]	Finite Volume Method	CFD fundamentals
[41]	Computational Fluid Dynamics	Numerical solution methods

7. Research Challenges and Future Perspectives

Despite significant advances in thermal insulation technologies, heat transfer analysis, and numerical modeling techniques, several challenges continue to limit the optimal thermal management of oil storage tanks. Addressing these challenges is essential for improving energy efficiency, operational safety, and long-term sustainability in petroleum storage facilities.

7.1 Limitations of Current Insulation Systems

Conventional insulation materials such as mineral wool, glass wool, and polyurethane foam remain widely used in industrial storage applications due to their relatively low cost and established performance. However, these materials may experience degradation over time as a result of aging, mechanical damage, moisture penetration, and environmental exposure [26, 27]. Moisture accumulation is particularly problematic because it increases effective thermal conductivity and

reduces insulation efficiency. In long-term service conditions, insulation performance may differ significantly from laboratory measurements, leading to higher heat losses than originally predicted [27]. Furthermore, insulation systems installed in harsh environments such as coastal regions, desert climates, and offshore facilities are exposed to severe thermal and environmental stresses that may accelerate performance deterioration.

7.2 Challenges in Thermal Performance Prediction

Accurate prediction of thermal behavior in oil storage tanks remains a complex engineering problem. Heat transfer processes involve simultaneous conduction, convection, and radiation mechanisms that interact under continuously changing environmental conditions [23, 40]. Although CFD models have significantly improved predictive capabilities, uncertainties still exist regarding boundary condition specification, turbulence modeling, solar radiation effects, and thermophysical property variations of stored petroleum products [38, 39]. Additionally, most existing studies focus on specific operating scenarios, making it difficult to generalize results across different tank geometries, climatic conditions, and petroleum products. Consequently, further validation using field measurements and long-term monitoring data remains necessary.

7.3 Integration of Smart Monitoring Technologies

Recent advances in sensing and data acquisition technologies offer new opportunities for improving insulation performance assessment. Wireless sensors, infrared thermography, and distributed temperature monitoring systems enable continuous observation of thermal conditions in industrial storage facilities. The integration of real-time monitoring with predictive numerical models can facilitate early detection of insulation degradation, abnormal heat losses, and operational inefficiencies. Such approaches support condition-based maintenance strategies and reduce the likelihood of unexpected thermal performance failures. Emerging digital twin technologies are particularly promising because they combine physical monitoring systems with real-time numerical simulations, providing a dynamic representation of tank thermal behaviour throughout the operational lifecycle [36].

7.4 Advanced Insulation Materials and Sustainable Solutions

Future developments in thermal insulation are expected to focus on advanced materials that provide superior thermal performance while minimizing environmental impact. Aerogel-based insulation materials, vacuum insulation panels, and high-performance composite systems have demonstrated considerable potential for reducing heat losses beyond the capabilities of conventional materials [29, 30]. At the same time, increasing attention is being directed toward environmentally sustainable insulation solutions. Future research should investigate recyclable, low-carbon, and bio-based insulation materials capable of meeting industrial performance requirements while supporting global sustainability objectives.

The development of multifunctional insulation systems combining thermal protection, moisture resistance, fire safety, and structural durability may also represent an important direction for future industrial applications.

7.5 Artificial Intelligence and Data-Driven Optimization

Artificial intelligence (AI) and machine learning techniques are increasingly being applied to thermal engineering problems. These technologies can analyze large operational datasets, identify hidden patterns, and predict system performance with reduced computational effort compared with

conventional simulation approaches [38]. In oil storage applications, AI-assisted optimization may support the selection of insulation materials, determination of optimum insulation thickness, prediction of heat losses, and scheduling of maintenance activities. Coupling machine learning algorithms with CFD simulations could significantly accelerate design optimization and improve decision-making processes. As industrial facilities continue to adopt Industry 4.0 technologies, data-driven thermal management strategies are expected to play an increasingly important role in future petroleum storage systems.

7.6 Future Research Directions

Based on the reviewed literature, several priority areas for future investigation can be identified:

- Development of coupled thermo-hygro-mechanical models that simultaneously consider heat transfer, moisture transport, and structural effects.
- Experimental validation of CFD predictions using large-scale oil storage tank measurements.
- Investigation of advanced insulation materials under realistic industrial operating conditions.
- Integration of artificial intelligence techniques with thermo-economic optimization methods.
- Development of digital twin frameworks for real-time monitoring and predictive maintenance.
- Evaluation of insulation performance under extreme climatic conditions associated with climate change.

Addressing these research needs will contribute to the development of safer, more energy-efficient, and economically sustainable oil storage systems [41].

7.7 Summary

Although considerable progress has been achieved in thermal insulation technologies and thermal analysis methods, several technical and practical challenges remain. Future developments are expected to focus on advanced insulation materials, smart monitoring technologies, artificial intelligence, and digital twin systems. These innovations have the potential to significantly improve energy efficiency, thermal performance, operational reliability, and environmental sustainability in oil storage tank applications.

8. Conclusions

Thermal insulation plays a fundamental role in improving the energy efficiency, thermal performance, and operational safety of oil storage tanks. This review has examined the main heat transfer mechanisms governing thermal behaviour in storage tanks, including conduction, convection, and radiation, and highlighted their influence on heat losses, temperature distribution, and overall system performance.

The review demonstrated that the selection of appropriate insulation materials is a critical factor in achieving effective thermal protection. Conventional materials such as mineral wool, glass wool, and polyurethane foam continue to be widely applied because of their practical performance and economic viability. At the same time, advanced insulation technologies, including aerogel-based materials and high-performance composites, offer significant opportunities for further reductions in heat losses and improvements in thermal efficiency. The analysis of insulation thickness

optimization revealed that thermal design should not rely solely on heat transfer considerations. Instead, thermo-economic approaches are necessary to identify insulation configurations that minimize total lifecycle costs while maintaining acceptable thermal performance. The reviewed studies consistently showed that optimal insulation thickness depends on operating temperature, environmental conditions, energy prices, and system service life.

The review further highlighted the importance of thermal insulation in reducing temperature fluctuations, limiting thermal stratification, preserving product quality, and decreasing energy consumption in oil storage facilities. Environmental factors such as ambient temperature, solar radiation, wind speed, and humidity were found to significantly affect thermal performance and should therefore be considered during insulation design and evaluation.

Numerical modeling and Computational Fluid Dynamics (CFD) have emerged as powerful tools for analyzing heat transfer processes and evaluating insulation effectiveness under realistic operating conditions. Recent advances in CFD techniques have enabled detailed investigation of transient thermal behavior, multiphase heat transfer, and environmental interactions, providing valuable insights that are difficult to obtain through experimental studies alone.

Despite substantial progress in insulation technologies and thermal analysis methods, several challenges remain. These include the long-term effects of moisture accumulation, insulation aging, uncertainties in thermal performance prediction, and the need for comprehensive field validation of numerical models. Emerging technologies such as artificial intelligence, machine learning, smart sensing systems, and digital twin platforms offer promising opportunities for addressing these challenges and improving future thermal management strategies.

Overall, effective thermal insulation represents one of the most practical and economically attractive approaches for reducing energy losses and enhancing the sustainability of petroleum storage operations. Future research should focus on advanced insulation materials, integrated thermo-economic optimization frameworks, coupled heat–moisture modeling, and intelligent monitoring systems to support the development of safer, more energy-efficient, and environmentally sustainable oil storage facilities.

References

- [1] Myers, P. E. (1997). *Aboveground Storage Tanks* (2nd ed.). McGraw-Hill.
- [2] Myers, P. E., & Lazzara, J. M. (2000). *Aboveground Storage Tanks* (3rd ed.). McGraw-Hill.
- [3] Sun, W., Li, M., Liu, Y., et al. (2023). Study of main factors influencing unsteady-state temperature drop in oil tank storage under dynamic thermal environment coupling. *Petroleum Science*, 20(6), 3783–3797.
- [4] Liu, Y., Fan, J., & Cheng, Q. (2018). Mathematical modeling of large floating roof oil tank temperature fields. *Polish Journal of Chemical Technology*, 20(1), 67–74.
- [5] Li, W., Zhang, X., Yu, G., & Wang, M. (2019). Numerical study on oil temperature field during long storage in large floating roof tank. *International Journal of Heat and Mass Transfer*, 130, 175–186. <https://doi.org/10.1016/j.ijheatmasstransfer.2018.10.024>
- [6] Kaynakli, O. (2014). Economic thermal insulation thickness for pipes and ducts: A review study. *Renewable and Sustainable Energy Reviews*, 30, 184–194.
- [7] Kaynakli, O. (2014). Economic thermal insulation thickness for pipes and ducts: A review study. *Renewable and Sustainable Energy Reviews*, 30, 184–194.
- [8] Alrasheed, M. R. A. (2024). Optimizing multilayer thermal insulation thickness on industrial pipelines. *Processes*, 12(2), 318.

- [9] Bao, Y., Zhang, F., Cheng, J., et al. (2023). Simulation on heat transfer and emergency protection of tanks in a tank farm under fire scenario. *International Journal of Environmental Research and Public Health*, 20(7), 5348.
- [10] Dombaycı, Ö. A. (2007). The environmental impact of optimum insulation thickness. *Building and Environment*, 42(11), 3855–3859.
- [11] Baetens, R., Jelle, B. P., & Gustavsen, A. (2011). Aerogel insulation for building applications: A state-of-the-art review. *Energy and Buildings*, 43(4), 761–769.
- [12] Karamanos, A., Hadjirakou, S., & Papadopoulos, A. M. (2008). The impact of temperature and moisture on the thermal performance of stone wool. *Energy and Buildings*, 40(8), 1402–1411.
- [13] National Fire Protection Association. (2022). *NFPA 30: Flammable and Combustible Liquids Code*. [NFPA Official Website](https://www.nfpa.org/standards)
- [14] Szcześniak, A., Milewski, J., et al. (2023). Determination of thermocline heat transfer coefficient using CFD simulation. *Energies*, 16(7), 3150.
- [15] Kocijel, L., Mrzljak, V., & Glažar, V. (2020). Numerical analysis of temperature stratification in large volumetric heat storage tanks. *Energy*, 194, 116878.
- [16] Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2011). *Fundamentals of Heat and Mass Transfer* (7th ed.). Wiley.
- [17] Çengel, Y. A., & Ghajar, A. J. (2015). *Heat and Mass Transfer: Fundamentals and Applications* (5th ed.). McGraw-Hill.
- [18] Sun, W., Li, M., Liu, Y., et al. (2023). Study of main factors influencing unsteady-state temperature drop in oil tank storage under dynamic thermal environment coupling. *Petroleum Science*, 20(6), 3783–3797.
- [19] <https://authorizedinspector.com/api-650-vs-api-653-what-is-the-difference/>
- [20] Kaynakli, O. (2014). Economic thermal insulation thickness for pipes and ducts: A review study. *Renewable and Sustainable Energy Reviews*, 30, 184–194.
- [21] Holman, J. P. (2010). *Heat Transfer* (10th ed.). McGraw-Hill.
- [22] Li, W., Zhang, X., Yu, G., & Wang, M. (2019). Numerical study on oil temperature field during long storage in large floating roof tank. *International Journal of Heat and Mass Transfer*, 130, 175–186.
- [23] Duffie, J. A., & Beckman, W. A. (2013). *Solar Engineering of Thermal Processes* (4th ed.). Wiley.
- [24] Liu, Y., Fan, J., & Cheng, Q. (2018). Mathematical modeling of large floating roof oil tank temperature fields. *Polish Journal of Chemical Technology*, 20(1), 67–74.
- [25] Alrasheed, M. R. A. (2024). Optimizing multilayer thermal insulation thickness on industrial pipelines. *Processes*, 12(2), 318.
- [26] Kaynakli, O. (2014). Economic thermal insulation thickness for pipes and ducts: A review study. *Renewable and Sustainable Energy Reviews*, 30, 184–194.
- [27] Jerman, M., Keppert, M., Výborný, J., & Černý, R. (2013). Hygric, thermal and durability properties of modern thermal insulation materials. *Construction and Building Materials*, 41, 352–359.
- [28] Karamanos, A., Hadjirakou, S., & Papadopoulos, A. M. (2008). The impact of temperature and moisture on the thermal performance of stone wool. *Energy and Buildings*, 40(8), 1402–1411.
- [29] Baetens, R., Jelle, B. P., & Gustavsen, A. (2011). Aerogel insulation for building applications: A state-of-the-art review. *Energy and Buildings*, 43(4), 761–769.

- [30] Jelle, B. P., Gustavsen, A., & Baetens, R. (2010). The path to the high-performance thermal building insulation materials and solutions of tomorrow. *Journal of Building Physics*, 34(2), 99–123.
- [31] Bao, Y., Zhang, F., Cheng, J., Li, H., & Wang, J. (2023). Simulation on heat transfer and emergency protection of tanks in a tank farm under fire scenario. *International Journal of Environmental Research and Public Health*, 20(7), 5348.
- [32] Kaynakli, O. (2012). A review of the economical and optimum thermal insulation thickness for building applications. *Renewable and Sustainable Energy Reviews*, 16(1), 415–425.
- [33] Dombaycı, Ö. A. (2007). The environmental impact of optimum insulation thickness for external walls of buildings. *Building and Environment*, 42(11), 3855–3859.
- [34] Hasan, A. (1999). Optimizing insulation thickness for buildings using life cycle cost. *Applied Energy*, 63(2), 115–124.
- [35] Dylewski, R., & Adamczyk, J. (2011). Economic and environmental benefits of thermal insulation of building external walls. *Building and Environment*, 46(12), 2615–2623.
- [36] Bolattürk, A. (2008). Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey. *Building and Environment*, 43(6), 1055–1064.
- [37] Ahmad, T., Zhang, D., Huang, C., Zhang, H., Dai, N., Song, Y., & Chen, H. (2021). Artificial intelligence in sustainable energy industry: Status quo, challenges and opportunities. *Journal of Cleaner Production*, 289, 125834.
- [38] Sun, W., Li, M. Y., Liu, Y. D., Cheng, Q. L., Zhao, L. X., Shao, S., & Wang, Z. H. (2023). Study of main factors influencing unsteady-state temperature drop in oil tank storage under dynamic thermal environment coupling. *Petroleum Science*, 20(6), 3783–3797.
- [39] Zhang, Y., Wang, X., Li, H., et al. (2025). Heat transfer research on the cooling process of waxy crude oil storage in the vault tank based on VOF model. *Applied Thermal Engineering*, 258, 124657.
- [40] Versteeg, H. K., & Malalasekera, W. (2007). *An Introduction to Computational Fluid Dynamics: The Finite Volume Method* (2nd ed.). Pearson Education.
- [41] Ferziger, J. H., & Perić, M. (2020). *Computational Methods for Fluid Dynamics* (4th ed.). Springer.