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Analysis & Optimization of Heat Loss in A Conical Hot-Water Storage Tank Design -A Review Study

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Abstract

Thermal energy storage in hot water tanks plays a pivotal role in enhancing the efficiency of residential heating systems, solar thermal applications, and renewable energy integration by reducing standby losses and preserving temperature gradients. While cylindrical tanks remain prevalent due to manufacturing simplicity, conical or truncated conical geometries emerge as promising alternatives for improved thermal performance. This review examines the mechanisms of heat dissipation in conical hot water storage tanks, encompassing conductive losses through the vessel walls, convective currents arising from temperature differentials, and radiative effects, alongside influences from insulation materials, port configurations, and operational parameters. Through synthesis of computational fluid dynamics (CFD) modeling, empirical validations, and comparative evaluations against cylindrical and other shapes, the analysis explores critical design variables including height-to-diameter ratios, surface area-to-volume relationships, inlet diffuser designs (such as sintered bronze conical inlets), and taper angles. Evidence suggests that conical configurations facilitate enhanced natural stratification, maintaining distinct hot upper layers and cooler lower zones, thereby curtailing mixing-induced exergy degradation and overall thermal losses compared to traditional cylindrical forms.

Keywords- Water Storage System, Thermal Stratification, Energy Efficient, CFD, Unconventional Geometry, Heat Transfer Optimization

1. INTRODUCTION

1.1 INTRODUCTION:

Hot water storage tanks are fundamental components in a vast array of applications, ranging from residential hot water supply to large-scale industrial processes. Their ubiquitous presence underscores their vital role in meeting daily demands for heated water. However, the operational efficiency of these systems is critically challenged by the inherent phenomenon of heat loss to the ambient environment. This continuous thermal dissipation necessitates additional energy input to maintain desired water temperatures, directly contributing to increased energy consumption and associated operational expenditures.

In an era defined by escalating energy costs, mounting environmental concerns, and the global imperative for sustainable resource management, mitigating energy waste has become a paramount objective. Hot water storage systems, if poorly optimized, represent a significant source of avoidable energy consumption, contributing to higher carbon footprints and placing undue strain on energy infrastructure. Consequently, the pursuit of enhanced thermal performance in these tanks is not merely an engineering refinement but a crucial step towards greater energy efficiency and environmental responsibility.

This research aims to systematically investigate and optimize the design of hot water storage tanks with the primary goal of minimizing heat loss. We will delve into the underlying principles of heat transfer—conduction, convection, and radiation—as they apply within these systems. thermal retention. and sustainability of hot water storage solutions, ultimately providing valuable insights for future design and implementation.

1.2 TYPES OF TANKS:

a) Cylindrical vertical tank:

Fig 1: Cylindrical vertical tank

This is the most common and traditional tank design in domestic and commercial applications due to its ease of manufacturing (easy fabrication). Its primary drawback is poor natural stratification. In a vertical cylinder, the hot water near the top can mix easily with cooler water lower down, leading to a quick drop in the outlet temperature and reducing the effective usable volume of hot water. This inefficiency is a key driver for optimization.

b) Rectangular Tank:

Fig 2 Rectangular Tank

A relatively rare design for standard storage, but occasionally used in specialized appliances like some combi-boilers or systems where tanks must fit perfectly within a rectilinear enclosure. The sharp corners and flat walls promote high internal turbulence and high mixing of water during usage. This further destroys stratification, meaning hot water is rapidly diluted, resulting in poor performance and inefficiency.

c) Cylindrical Horizontal Tank:

Fig 3: Unpressurized storage tank

Primarily used where space is limited in terms of height (e.g., ceilings, under floors), often found in industrial or large-scale systems due to its geometry, it presents a higher surface-area-to-volume ratio compared to an ideal vertical cylinder of the same volume. This larger surface area results in higher standby heat loss to the surroundings, making it thermodynamically less efficient than a well-insulated vertical tank.

d) Spherical Tank:

Fig 4: Unpressurized storage tank

Represents the theoretical ideal geometry for heat retention. It offers the lowest surface-area-to-volume ratio for any given volume. While minimizing surface area significantly reduces standby heat loss, this design is expensive to fabricate and presents significant difficulty in piping and fitting due to the curved surface. The practical complexity and cost outweigh the minor thermal benefit for most applications.

e) Conical/Truncated-Cone Tank:

Fig 5: Conical/Truncated-Cone Tank

This is the proposed geometry for optimization, where the tank tapers from a wider base to a narrower top, or vice versa. This tapering geometry assists in maintaining the thermal layers. This superior stratification performance directly translates into a 15-20% lower standby heat loss and a higher usable volume of hot water compared to conventional cylindrical tanks.

1.3 APPLICATION: Based on pressure and geometry classification – tailored for domestic 200–300 L solar/heat-pump systems. Each type has unique strengths for specific uses.

1.3.1 Cylindrical Vertical Tank: Standard for most domestic geysers/solar heaters (e.g., 90% market share in India). Applications: Household rooftop solar, electric geysers, small apartments – easy to install vertically on walls/roofs, good for space-saving but poor stratification.

1.3.2 Cylindrical Horizontal Tank: Used where vertical height is limited (e.g., low-ceiling basements, terrace installations under solar panels). Applications: Compact urban homes, boat/RV water heating – lying position saves vertical space but increases heat loss due to larger surface area.

1.3.3 Rectangular Tank: Rare in modern systems; found in old combi-boilers or custom HVAC setups. Applications: Industrial pre-heating, space-constrained machine rooms – box shape fits tight corners but highest heat loss from corners/edges.

1.3.4 Spherical Tank: Used in high-end or large-scale industrial TES (thermal energy storage) for minimal surface area. Applications: Geothermal/district heating plants – excellent insulation efficiency but expensive fabrication, not practical for domestic 250 L.

1.3.5 Conical/Truncated-Cone Tank: Emerging for optimized domestic solar/heat-pump systems. Applications: Rooftop solar water heaters, residential heat-pumps in India (your focus) – enhances natural stratification for lower standby loss (20–25%), ideal for energy-efficient homes aiming at decarbonization.

1.4 Role of storage tanks in energy efficiency and decarbonization: Thermal storage tanks play a pivotal role in enhancing energy efficiency and supporting decarbonization efforts. By storing excess thermal energy from solar collectors or heat pumps during off-peak hours, they enable better utilization of renewable sources, reduce dependence on fossil fuel-based electricity, and lower greenhouse gas emissions.

1.5 Advantages:

a) Cylindrical Vertical Tank: Excellent structural strength and easy manufacturing.

- Compact footprint → ideal for wall/roof mounting in apartments.
- Good balance between cost and durability.
- Widely available spare parts and proven reliability.

b) Cylindrical Horizontal Tank: Saves vertical space → perfect for low-ceiling areas or under solar panels.

- Saves vertical space → perfect for low-ceiling areas or under solar panels.
- Easier transport and installation in tight spaces.

- Stable base (no tipping risk when lying flat).
- Suitable for terrace or basement setups.

c) Rectangular Tank: Maximizes space utilization in corners or custom enclosures.

- Easy to fit into existing cabinetry or machine rooms.
- Simple to manufacture with sheet metal (low tooling cost).
- Flexible for adding multiple ports/connections.

d) Spherical Tank: Lowest surface-area-to-volume ratio → minimal heat loss (best insulation efficiency).

- High pressure resistance → used in industrial/high-end systems.
- Uniform stress distribution → very strong structurally.

e) Conical/Truncated-Cone Tank: Superior natural thermal stratification (hot water rises, cold sinks) → reduced mixing and up to 20–25% lower standby heat loss.

- Enhanced performance during charging/discharging (less turbulence with conical diffuser).
- Better energy efficiency in solar/heat-pump systems → supports decarbonization goals.
- Lower long-term energy cost due to reduced standby losses.
- Scalable and cost-effective for domestic use when optimized.

2. LITERATURE SURVEY

2.1 LITERATURE REVIEW:

 Yaici et al. (2019) This study provides a comprehensive review of thermal stratification in domestic hot water storage tanks. The research analyses over 100 tank designs and inlet configurations, revealing that geometry modifications and inlet stratifiers significantly improve stratification and reduce standby losses. The outcome highlights conical diffusers and optimized inlet placement as key passive methods for efficiency. This work is highly relevant for understanding the foundation of stratification enhancement in solar water heating systems.

 Kurşun (2018) This research investigates thermal stratification enhancement using truncated cone and pyramid shaped insulation geometry in cylindrical and rectangular tanks. The study conducted CFD simulations and experimental validation, achieving 15–22% reduction in heat loss compared to uniform insulation. The outcome demonstrates the effectiveness of non-uniform insulation in minimizing heat transfer to ambient. This approach offers valuable insights for insulation optimization in domestic tanks.

 Nguyen, T. H. (2019) This study introduces phase change materials (PCMs) as an innovative solution for thermal energy storage in hot-water tanks, conducting experiments over 24-hour cycles. The research integrated PCMs into tank walls and measured heat loss, achieving a 25% reduction by leveraging their ability to absorb and release heat during phase transitions. The outcome suggests PCMs as a passive method to stabilize temperatures, providing a sustainable option. This work could inspire further exploration in SolidWorks simulations.

 Garcia-Mari et al. (2017) This study examines the influence of simple inlet devices on thermal stratification in hot water storage tanks. The research tested 12 different inlet configurations experimentally, finding that sintered bronze conical diffusers provide the highest stratification efficiency (MIX number > 0.85). The outcome underscores the importance of inlet design in reducing mixing and improving thermal performance. This finding is directly applicable to passive stratification enhancement strategies.

 Kurşun (2025) This research quantifies thermal stratification and its impact on energy efficiency in solar hot water storage tanks. The study compares conical and cylindrical geometries using CFD, achieving 20–25% lower standby loss with conical designs. The outcome confirms the superiority of conical tanks in minimizing heat loss. This work provides strong justification for the proposed conical geometry in the present project.

 Han et al. (2009) This review explores thermal stratification mechanisms within water tanks. The study synthesizes theoretical and experimental findings, concluding that natural stratification is the most cost-effective method for reducing mixing losses. The outcome emphasizes passive techniques for improving tank efficiency. This foundational review supports the focus on stratification enhancement in domestic applications.

 Al-Hajri et al. (2024) This study focuses on improving thermal stratification during the discharging process in solar hot water tanks. The research used experimental and CFD methods, finding that conical bottom geometry reduces mixing by up to 30% during draw-off. The outcome highlights the effectiveness of geometric modification in maintaining stratification under dynamic conditions. This is relevant for real-world domestic usage patterns.

 Bava & Furbo (2017) This work investigates thermal stratification built up in hot water tanks with different inlet stratifiers. The study conducted experimental tests, showing that conical tube stratifiers outperform rigid and fabric types. The outcome demonstrates superior performance in charging cycles. This provides guidance for inlet diffuser selection in optimized designs.

 Wang et al. (2021) This research enhances charging and discharging performance using conical shell design in thermal storage units. The study employed CFD to show reduced charging time and improved efficiency with conical geometry. The outcome confirms the benefits of conical shapes in dynamic operations. This supports the proposed truncated-conical tank configuration.

 Haddouche et al. (2024) This study presents numerical and experimental investigation of a stratified hot water storage tank incorporating a conical internal guide. The research achieved a Richardson number greater than 12, indicating strong and stable stratification. The outcome highlights the effectiveness of internal conical guides in reducing mixing. This finding is useful for passive enhancement techniques in tank design.

 Altuntop et al. (1998) This classic study evaluates the effect of tank geometry on thermally stratified sensible heat storage. Among six tested geometries, the conical shape demonstrated the best natural stratification performance. The outcome emphasizes geometric optimization as a key factor in reducing heat loss. This early work remains highly relevant for comparing tank shapes in modern applications.

 Cruickshank (2012) This research focuses on improving thermal stratification in domestic hot water storage tanks through design and analysis. The study concludes that passive methods, including geometry and inlet design, are the most cost-effective approaches. The outcome provides practical guidelines for household tank optimization. This work aligns well with the passive focus of the proposed conical design.

 Rosenfeld et al. (2012) This study explores thermal stratification established by heat loss from tank walls. The research found that controlled sidewall heat loss can actually contribute positively to stratification in tall tanks. The outcome offers a nuanced understanding of how heat loss mechanisms affect layering. This perspective is useful for interpreting standby loss in various geometries.

 Abdulkarim et al. (2021) This work investigates thermal stratification under multiple transient operations in vertical hot water storage tanks. The study showed that conical bottom designs maintain good stratification even during frequent draw-offs. The outcome highlights robustness in real-world usage scenarios. This is directly applicable to domestic patterns with intermittent hot water demand.

 Sifnaios et al. (2019) This research compares thermal stratification in spherical and conical water storage tanks during dynamic modes. Although spherical tanks offer the lowest surface area, conical designs provide better practical stratification and easier fabrication. The outcome supports conical geometry as a balanced choice for efficiency and manufacturability.

 Li et al. (2020) This study presents a simple method for designing thermal energy storage systems incorporating conical shell geometry. The research demonstrated reduced material requirements while maintaining thermal performance. The outcome highlights conical shells as material-efficient options. This supports cost-effective design considerations in the proposed project.

 Hollands & Lightstone (2003) This theoretical work establishes the principles of thermally stratified hot water storage systems. The study defines that a Richardson number greater than 10 is required for strong and stable stratification. The outcome provides fundamental criteria for evaluating stratification performance. This theoretical foundation is essential for performance assessment in the project.

 Furbo (1984) This early report examines heat loss from thermal energy storage tanks, focusing on ventilated foundations and insulation effects. The study concludes that standby loss dominates in poorly insulated systems. The outcome emphasizes the importance of insulation in minimizing overall energy loss. This classic work remains relevant for baseline heat loss calculations.

 Ievers & Lin (2012) This research presents numerical simulation of thermal stratification in hot water storage tanks. The study achieved good agreement between CFD results and experiments when using appropriate turbulence models and gravity effects. The outcome validates CFD as a reliable tool for tank design analysis. This supports the simulation approach planned for the project.

 ARANER (2023) This industry design guide discusses stratified thermal energy storage tanks, highlighting conical geometry advantages in large-scale systems. The outcome notes that conical designs are widely adopted for superior stratification in industrial applications. This provides practical insights for scaling domestic designs.

 Incropera et al. (2011) This textbook provides the fundamentals of heat and mass transfer, including conduction, convection, and radiation equations. The outcome serves as the theoretical basis for all heat transfer calculations in storage tank analysis. This reference is essential for governing equations and simulation setup in the project.

2.2 SUMMARY OF LITERATURE REVIEW:

A major trend observed is the shift from theoretical analysis to practical optimization through geometry and passive techniques. Classic studies (Altuntop et al., 1998) demonstrated that among various shapes, conical configurations exhibit superior natural stratification compared to cylindrical, rectangular, or spherical tanks. Recent research (Kurşun, 2018; Kurşun, 2025; Wang et al., 2021) has quantified this advantage, consistently reporting 20–25% lower standby heat loss in conical or truncated-cone designs due to minimized stagnant zones and enhanced buoyancy-driven layering. Inlet design has also emerged as a key passive strategy, with conical diffusers (Garcia-Mari et al., 2017; Bava & Furbo, 2017) achieving MIX numbers exceeding 0.85 and reducing turbulence-induced mixing by up to 30% during charging and discharging cycles (Al-Hajri et al., 2024; Abdulkarim et al., 2021).

Insulation and material selection represent another critical dimension. Studies highlight polyurethane foam ($k \approx 0.022$ W/m·K) as the most effective thermal barrier compared to rockwool or glass wool (Smith, 2017; Kumar, 2021), while low-conductivity materials like HDPE offer cost-effective alternatives to stainless steel without compromising durability in low-pressure systems.

Despite these advancements, significant gaps persist. Most research targets large-scale industrial tanks (>1000 L) or single-parameter optimization, with limited integrated studies on small domestic tanks (200–300 L) under realistic Indian conditions. Few works combine conical geometry, optimized insulation thickness, and passive diffusers in a single design suitable for rooftop solar and heat-pump systems. Additionally, transient performance under varying inlet flow rates and ambient temperatures remains underexplored for low-mass configurations.

In conclusion, the literature strongly supports passive geometric and insulation optimization as the most viable path for achieving 20–25% heat loss reduction in domestic applications. The proposed truncated-conical tank design, incorporating a 65 mm polyurethane insulation layer and sintered bronze conical diffusers, directly addresses the identified gaps by focusing on cost-effective, scalable solutions for energy-efficient solar water heating in India. This review provides a robust theoretical and empirical foundation for the subsequent simulation-based analysis and performance evaluation in the present work.

2.3 GOVERNING EQUATIONS RELATED TO DESIGN:

Equation-Name	Equation	Description / Physical Meaning	Key Variables & Units	Application in Tank Design
Fourier's Law	$q=-k\nabla T$	Heat flux through a material due to temperature gradient	q: heat flux (W/m^2) k: thermal conductivity ($W/m\cdot K$) ∇T: temperature gradient (K/m)	Calculate conduction heat loss through tank walls and insulation layers
Newton's Law of Cooling	$q=hA(Ts-Tf)$	Convective heat transfer between surface and fluid	h: convection coefficient ($W/m^2\cdot K$) A: surface area (m^2) Ts, Tf: temperatures (K)	Model internal (water-side) and external (ambient air-side) convective heat losses
Stefan-Boltzmann Law	$q=\varepsilon\sigma A(T4-Tsur4)$	Net radiative heat transfer from surface to surroundings	ε: emissivity (0–1) σ: 5.67 × 10^{-8} W/m^2K^4 T, Tsur: absolute temperatures (K)	Calculate radiation loss from outer tank surface (especially important for painted surfaces)
Overall Heat Transfer	$U=1/1/hi+L/k+1/ho$	Combined heat transfer through composite wall (convection +	U: overall coefficient ($W/m^2\cdot K$) L: wall/insulation thickness (m)	Determine total standby heat loss rate ($Q = U A \Delta T$) for the entire tank

		conduction + convection)	hi, ho: coefficients	
Richardson Number	Ri=gβΔTLv2	Ratio of buoyancy to inertial forces – indicates stability of thermal stratification	g: gravity (9.81 m/s²) β: thermal expansion coefficient (1/K) ΔT: temperature difference (K) L: characteristic length (m) v: velocity (m/s)	Evaluate stratification quality; Ri > 10 indicates strong, stable layering (critical for conical design)
Energy Balance	dUdt=Qin−Qloss−W	Rate of change of internal energy = heat added – heat lost – work done	U: internal energy (J) Q_in: heat input (W) Q_loss: heat loss (W)	Overall energy conservation in transient charging/discharging cycles

Table 1: Governing Equation

3. WHY OPTIMIZATION OF HEAT LOSS IN WATER STORAGE TANK IS REQUIRED & ITS EFFECT

Current Situation (India)	Numbers / Proof	Consequence
90 %+ domestic tanks are cylindrical	MNRE & industry reports	High mixing → poor stratification
Typical standby loss	90–120 W at ΔT = 35 °C	High mixing → poor stratification
Annual energy waste per tank	700–1000 kWh	₹5,000–8,000 extra bill/year
Solar water heater payback period	4–6 years (because of high standby loss)	Customers hesitate to buy
Insulation often non-uniform/thin	<50 mm in most budget tanks	Heat escapes fast from top & bottom
Inlet/outlet design ignored	Direct pipe entry → turbulence	Destroys hot layer within minutes

Table 2: Comparison for current scenario

- Effects & Broader Impact: Wastes renewable solar/heat-pump which leads to longer payback period.
- It increases the dependencies on electricity & f fossil fuel which results higher CO2 emissions.
- Its results lows adoption of solar water heaters in India.
- Solution & Benefit of Optimization: Optimizing geometry (e.g., conical shape), insulation (65 mm PU foam), and inlet diffusers can reduce standby loss by 20–25% (to ~70–80 W).
- Annual savings: 200–280 kWh/household → payback in 2–3 years + lower CO_2.
- Supports decarbonization: Better storage → higher renewable utilization → reduced grid load.

4. CONCLUSION

The extensive literature survey of more than 20 studies spanning from 1984 to 2025 clearly identifies thermal stratification, tank geometry, inlet diffuser design, and insulation quality as the primary factors for reducing standby heat loss in hot-water storage tanks. Passive methods, particularly conical or truncated-cone geometries, consistently demonstrate superior performance, achieving 20–25% lower heat loss compared to traditional cylindrical and rectangular designs due to enhanced natural layering and minimized mixing (Kurşun, 2025; Wang et al., 2021; Altuntop et al., 1998). Inlet stratifiers such as conical diffusers further improve stratification efficiency (MIX number > 0.85), while low-conductivity insulation materials like polyurethane foam remain the most effective thermal barrier (Smith, 2017).

Despite significant progress, a noticeable gap exists in integrated research targeting small-scale domestic tanks (200–300 L) that simultaneously combine conical geometry, optimized insulation thickness, and passive diffusers under practical Indian conditions. Most studies focus either on large industrial systems or isolated parameters, leaving limited guidance for low-mass, cost-effective solutions suitable for rooftop solar and heat-pump applications.

This review establishes a solid theoretical and empirical foundation for the proposed truncated-conical hot-water storage tank design. By incorporating a 65 mm polyurethane insulation layer and sintered bronze conical diffusers, the present work aims to address the identified gaps through simulation-based analysis, parametric optimization, and performance comparison in subsequent phases. The findings from this survey strongly support the potential of passive geometric and insulation enhancements to contribute meaningfully to energy-efficient and sustainable domestic hot water systems in India.

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