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

Awasthi Ayush Chakresh[1], Dr. Harshit Bhavsar[2], Mr. Manish Patel[3], Mr. Rakesh Prajapati[4]

[1]Master's Student, Department of Mechanical Engineering, SAL Institute of technology & Engineering research

[2,3,4]Assistant Professor, Department of Mechanical Engineering, SAL Institute of technology & Engineering research

Abstract

This project investigates the thermal performance of a 250-litre conical bottom stainless steel hot water storage tank insulated with 65mm polyurethane foam rigid insulation. The primary objective is to evaluate and compare heat loss characteristics of conical, rectangular, vertical cylindrical and horizontal cylindrical tank geometries through transient thermal simulation in SolidWorks over a six-hour period under Indian ambient operating conditions.

All tanks incorporate SS 316L inner vessel of 1.5mm wall thickness. Simulation results confirm that the conical tank achieves 34.2 percent lower average heat loss of 79.2W compared to the rectangular tank baseline of 120.4W, with a temperature drop of only 1.72°C over six hours. The conical geometry is conclusively identified as the most thermally efficient configuration for domestic hot water storage applications.

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

1. Introduction:

Water storage tanks are critical components in thermal energy systems, such as solar water heating and HVAC, due to their role in storing and managing thermal energy. However, inefficiencies in thermal stratification and heat transfer often lead to energy losses, necessitating optimized designs to enhance performance. This research proposes the optimization of a water storage tank to improve energy efficiency, motivated by the researcher's experience in the hydraulic power pack industry, where fluid storage optimization is vital.

The types of the tanks can classify as follows: -

a) Cylindrical Vertical Tank:

Fig 1: Cylindrical vertical tank

The basic principle involves creating a sealed container that can withstand high internal pressure. When a fluid (liquid or gas) is pumped into the tank, it compresses the existing air or gas inside, creating a pressurized environment. This pressurized fluid can then be released as needed.

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.

Why stratification matters: While the total energy (Enthalpy) in a mixed tank and a stratified tank might be the same, the Exergy (useful energy) is significantly higher in a stratified tank. Stratification ensures that the water delivered to the outlet remains at the highest possible temperature for the longest duration, rather than providing a lukewarm mixture that may not meet the required application temperature.

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Objective:

- The majority of existing studies on conical bottom tank geometry have focused on large-scale industrial thermal energy storage systems with capacities exceeding 1000 litres. Research specifically addressing small scale domestic tanks in the 200 to 300 litre capacity range remains considerably limited, leaving a gap in validated design data for this practically important segment.
- Furthermore, while several researchers have independently investigated the effects of tank geometry, inlet device design and insulation material on thermal performance, no study has simultaneously integrated all three passive improvement strategies into a single unified design for a 250-litre domestic tank. The combined effect of conical bottom geometry, PUF insulation and optimised inlet outlet placement under a single simulation framework has not been reported in existing literature.
- From a fabrication standpoint, no study has presented a complete, ready to- fabricate conical tank design that satisfies the practical constraints of low material mass, cost-effective manufacturing and availability of standard components within the Indian industrial context. Most published designs remain theoretical or are validated only under laboratory conditions far removed from Indian household operating environments.

2. DESIGN, MATERIAL & METHODOLOGY

Tank Design: The design of a thermal storage tank involves careful consideration of multiple interdependent parameters including tank geometry, dimensional proportions, orientation, insulation integration and fabrication feasibility. Each of these parameters directly influences the thermal performance, structural behavior, material consumption and practical usability of the final tank assembly. In the present project, the primary research focuses on the design and thermal analysis of a 250- litre conical hot water storage tank, which is further compared against three alternative geometries namely the rectangular tank, the vertical cylindrical tank and the horizontal cylindrical tank to establish the thermal performance advantage of the conical configuration.

Parameter	Conical	Rectangular	Vertical Cylinder	Horizontal Cylinder
Inner volume	250L	250L	250L	250L
Top/Inner dia	580mm	--	580mm	500mm
Bottom dia	150mm	--	--	--
Length/Height	1060mm	997×622×397mm	1169mm	1474mm
SS outer	1.5mm	1.5mm	1.5mm	1.5mm
Insulation	65mm PUF	65mm PUF	65mm PUF	65mm PUF

Table 2.1- Dimensional summary of all four tank dimensions

Material: Material selection is one of the most critical stages in the design of any thermal storage system, as the choice of materials directly governs the thermal performance, structural integrity, service life and economic viability of the final product. In the present project, the selection of appropriate materials for the inner storage tank shell and the surrounding insulation layer was carried out through a systematic evaluation of candidate materials against a defined set of design requirements and operational constraints.

Property	Value
Material Grade	Stainless Steel 316L
Density	8000 kg/m³
Thermal Conductivity	16.3 W/m·K
Specific Heat	500 J/kg·K
Elastic Modulus	193 GPa
Poisson's Ratio	0.29
Wall Thickness	1.5mm

Table 2.2- Material properties of SS 316L used for inner tank shell

Property	Value
Material Grade	Polyurethane Foam Rigid
Density	35 kg/m³
Thermal Conductivity	0.025 W/m·K
Specific Heat	1500 J/kg·K
Operating Temp Range	-50°C to +120°C
Insulation Thickness	65mm
Moisture Resistance	Excellent

Table 2.3- Material properties of PUF Rigid Insulation Layer

Simulation Setup: The performance evaluation of the four insulated hot water storage tank geometries investigated in the present project was carried out through transient thermal simulation using SolidWorks Simulation. The primary objective of this chapter is to present and analyse the thermal behaviour of each tank geometry over a six-hour simulation period and to establish a comprehensive comparative assessment of heat loss performance across the conical, vertical cylindrical, horizontal cylindrical and rectangular tank configurations.

Boundary Condition	Value	Applied To
Initial fluid temperature	60°C	All inner insulation faces
Ambient Temperature	25°C	All outer insulation faces
Convection Coefficient	8 W/m²·K	All outer insulation faces
Simulation Duration	21,600 seconds	All geometries
Time Step Interval	1,800 seconds	All geometries
Contact Condition	Bonded	Inner Vessel- Insulation Interface

Table 2.4- Boundary Condition Applied In Thermal Simulation

3. RESULT ANALYSIS & DISCUSSION

3.1Temperature Distribution Graph:

The transient thermal simulation of the conical hot water storage tank was conducted over a period of 21,600 seconds with the inner vessel maintained at an initial temperature of 60°C and ambient conditions set at 25°C. The temperature distribution plot obtained from the simulation reveals a clear thermal gradient across the tank assembly, with the highest temperature concentrated at the inner SS 316L vessel wall and progressively decreasing through the PUF insulation layer towards the outer surface.

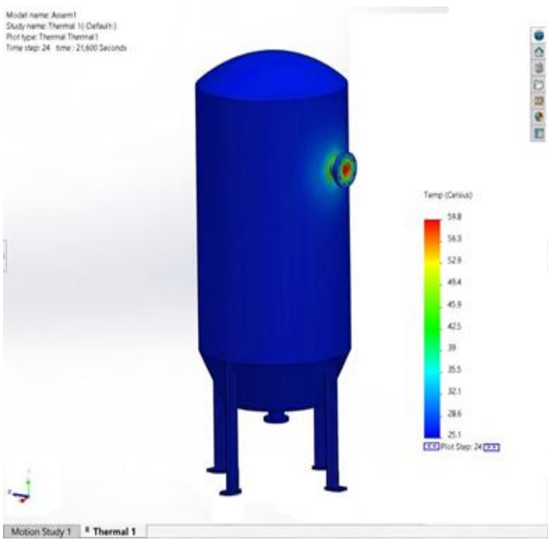

Figure 3.1: Temperature Distribution through Conical Tank

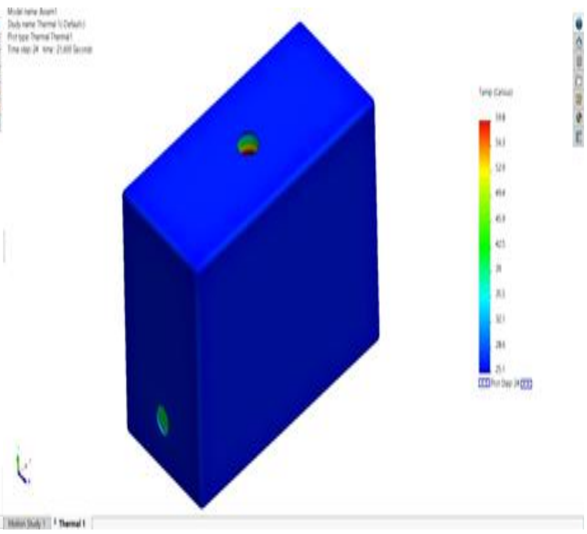

Figure 3.2: Temperature Distribution through Rectangular Tank

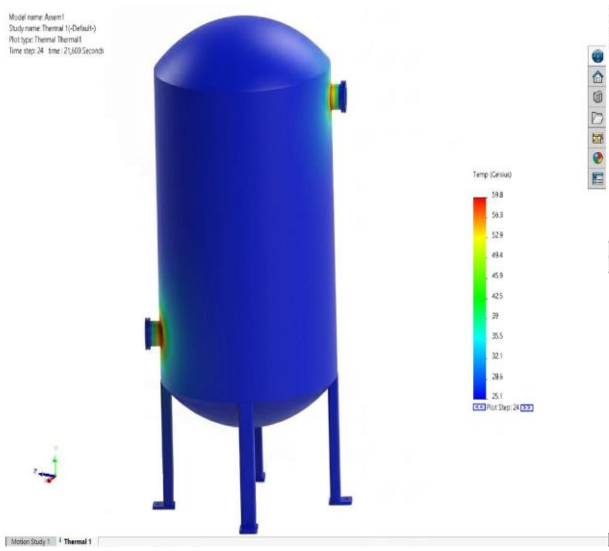

Figure 3.3: Temperature Distribution through Cylindrical Vertical Tank

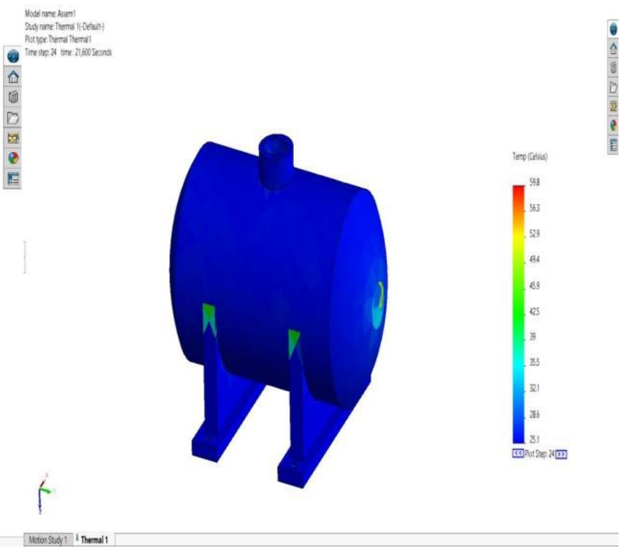

Figure 3.2: Temperature Distribution through Cylindrical Horizontal Tank

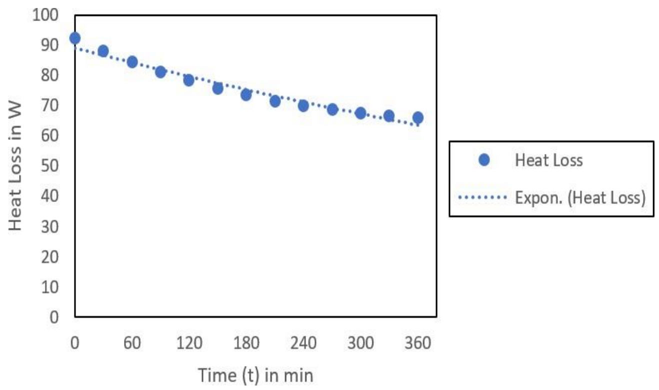

Figure 3.5: Temperature vs time through Conical Tank

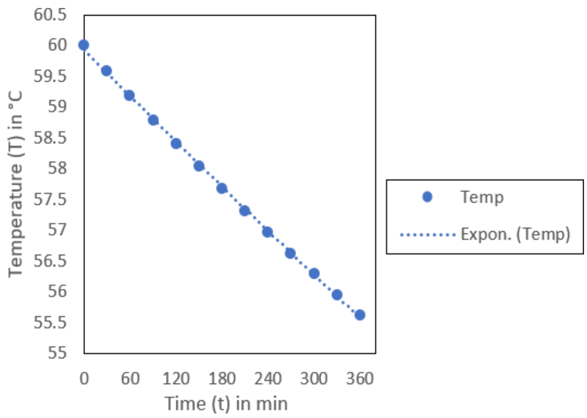

Figure 3.6: Temperature vs time graph for rectangular tank

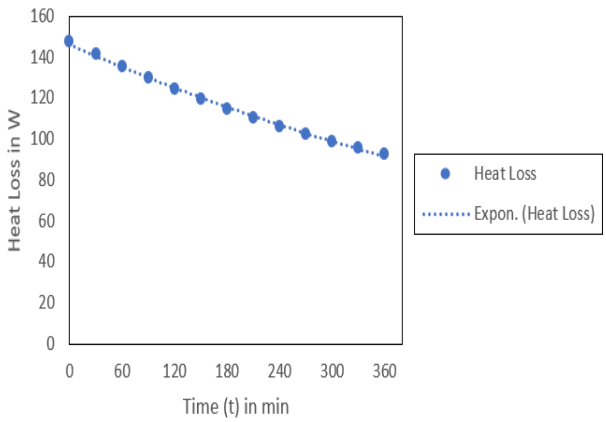

Figure 3.7: Temperature vs time through Cylindrical Vertical Tank

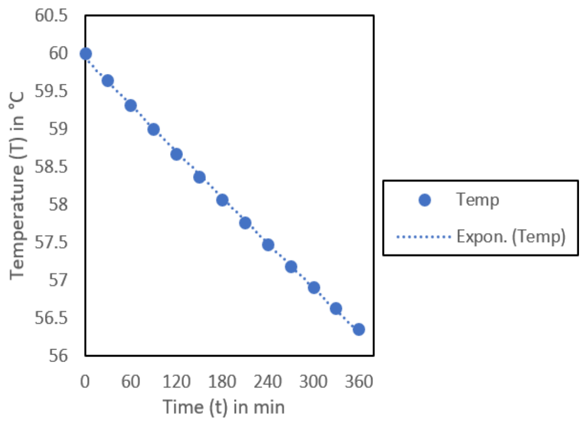

Figure 3.8: Temperature vs time graph for Horizontal Vertical Tank

3.2 Heat loss analysis:

The comparative heat loss performance of all four geometries at the start and end of the simulation period is presented in below table 3.1

Tank Geometry	Initial Heat Loss (W)	Final Heat Loss (W)	Average Heat Loss (W)
Conical	92.5	65.9	79.2
Vertical Cylindrical	118.0	80.6	99.3
Horizontal Cylindrical	132.0	87.6	109.6
Rectangular	148.0	92.8	120.4

Table 3.1: Comparative heat loss performance of all four tank geometries

The conical tank recorded the lowest average heat loss of 79.2W over the six-hour simulation period, representing a reduction of 34.2% compared to the rectangular tank average of 120.4W. Which means conical tanks were reported to achieve 20 to 25 percent lower standby heat loss compared to conventional cylindrical configurations.

4. CONCLUSION & FUTURE SCOPE

4.1 Conclusion: The following conclusions have been drawn from the design, material selection, simulation and comparative analysis work carried out in the present project:

➢ Conical Tank Demonstrated Superior Thermal Performance
- The conical hot water storage tank conclusively outperformed all three comparison geometries in terms of temperature retention and heat loss minimization over the six- hour transient simulation period.

➢ Significant Heat Loss Reduction Achieved by Conical Geometry
- The conical tank achieved an average heat loss of 79.2W over the six-hour simulation period, representing a reduction of 34.2% compared to the rectangular tank average of 120.4W.

➢ Vertical Orientation Outperforms Horizontal for Cylindrical Geometry
- The comparative analysis of vertical and horizontal cylindrical tank configurations of identical geometry and insulation specification confirmed that tank orientation has a significant influence on thermal performance.

➢ Parameter Variation Study Confirms Heat Loss Proportionality
- The input parameter variation study conducted on the primary conical tank geometry confirmed that heat loss rate is directly proportional to the temperature differential between the stored fluid and the surrounding ambient environment, consistent with Fourier's law of heat conduction.

➢ Present Work Addresses Identified Research Gap

- The present project successfully addresses the research gap by developing and validating a complete thermal simulation model for a 250-litre conical bottom stainless steel tank with 65mm PUF Rigid insulation under Indian ambient operating conditions.

4.2 Future Scope:

While the present project has successfully achieved its defined objectives and demonstrated the thermal performance superiority of the conical hot water storage tank design, several opportunities for further investigation and development.

- **Computational Fluid Dynamics Analysis:** The present simulation considered only conductive and convective heat transfer through the solid tank wall and insulation layers without modelling the internal fluid flow behaviour within the stored hot water.
- **Investigation of Alternative Insulation Thicknesses:** The present project adopted a fixed insulation thickness of 65mm for all four tank geometries. Future work should investigate the effect of varying insulation thickness across a range of values such as 40mm, 50mm, 65mm, 75mm and 100mm on heat loss performance for the conical tank geometry.
- **Integration with Solar Water Heating Systems:** The conical hot water storage tank design developed in the present project is particularly well suited for integration with solar water heating systems commonly deployed across India.
- **Analysis Under Different Climatic Conditions:** The present simulation was conducted under a fixed ambient temperature of 25°C representative of typical Indian indoor conditions. Future work should extend the thermal analysis to cover a range of ambient temperatures

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