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Numerical & Experimental Analysis of Transient Cooling of Cylinder

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Abstract:

Transient cooling of cylindrical objects is a crucial process in numerous industrial applications, including metal forming, electronics cooling, and food processing. Understanding the thermal dynamics during cooling is imperative for optimizing process parameters and ensuring product quality. This study integrates numerical simulations with experimental data to provide a detailed analysis of the transient cooling behaviour of a cylinder.
This research presents a comprehensive examination of the transient cooling of a cylindrical object, incorporating both numerical simulations and experimental investigations. The primary objective is to elucidate the thermal behaviour during the cooling process and to validate the numerical model with experimental data. The results offer valuable insights into heat transfer mechanisms and establish a foundation for optimizing cooling strategies in various engineering applications. A physical prototype of the cylindrical object is created, equipped with temperature sensors strategically placed to capture real-time data during the cooling process. Environmental factors, such as ambient temperature and coolant flow rates, are carefully controlled during experiments. The study demonstrates gradual temperature decreases from 299.9987 K to 296.8495 K at an initial temperature of 300 K, 349.99 K to 324.28 K at 350 K, and consistent cooling trends at 400 K (399.98 K to 352.21 K), 450 K (449.97 K to 380.67 K), and 500 K (499.97 K to 409.56 K).

Keywords: *Transient cooling, cylindrical objects, Industrial applications, Thermal dynamics, Process optimisation.*

Introduction:

Transient heat transfer in solids involves analyzing how temperature changes within a solid over time as heat is transferred through conduction, convection, and radiation. This analysis is crucial for various engineering applications, including cooling systems, thermal management, and material processing. Several factors must be considered to study this phenomenon effectively:

The geometry of the solid object and its material properties, such as thermal conductivity, specific heat capacity, and density, play a crucial role in determining heat transfer within the solid. The initial temperature distribution at the start of the simulation and the boundary conditions, including convective heat transfer coefficients or fixed temperature conditions, must be defined. The analysis must account for the three main heat transfer mechanisms: conduction, convection, and radiation. Conduction refers to heat transfer through the solid material, convection involves heat transfer due to fluid motion or forced air cooling, and radiation is the transfer of heat through electromagnetic waves.

Transient heat transfer in solids is governed by the heat diffusion equation, also known as the heat conduction equation, a partial differential equation that describes temperature changes over time and space within the solid. Numerical method such as the finite difference is used to solve these equations. COMSOL is used to set up the simulation, solve the equations, and visualize the results. Once the model is set up, the simulation can be run to obtain the temperature distribution within the solid over time. Post-processing involves analyzing and visualizing the results, which may include temperature profiles, contours, or transient plots. By simulating and studying transient heat transfer in solids, engineers can optimize designs, evaluate thermal performance, and make informed decisions regarding cooling strategies, material selection, and thermal management solutions.

Methodolgoy:

The methodology for the project "Numerical & Experimental Analysis of Transient Cooling of a Cylinder using COMSOL Software" is meticulously structured to ensure a thorough investigation of transient cooling phenomena. The initial phase defines the transient cooling problem in a cylindrical object and outlines the project's scope, including specific objectives, parameters, and materials to be studied. A comprehensive literature review follows, examining existing knowledge on transient cooling, heat transfer principles, and relevant numerical and experimental methodologies. This review identifies key theories, methodologies, and best practices from prior research, establishing a solid foundation for the study. Simulations are conducted for various scenarios, with parameters such as material properties, coolant flow rates, and initial temperatures systematically adjusted to explore different transient cooling conditions

Concurrently, the experimental setup is fabricated to match the numerical model closely. This involves constructing a physical prototype of the cylindrical object, strategically installing temperature sensors within the object, setting up data acquisition equipment for real-time data collection, and ensuring precise control of environmental conditions, including ambient temperature. The methodology culminates in a detailed comparison and validation process, where the numerical simulation results are rigorously compared with the experimental data to validate the accuracy of the numerical model.

Objectives Of Research:

The project objectives aim to deepen the understanding of transient cooling phenomena in cylindrical objects. They encompass numerical simulations using COMSOL Multiphysics software and experimental validations to ensure robust and accurate results.

1. To study the fundamentals of heat transfer along with transient analysis.
2. To carry out transient heat transfer analysis using COMSOL Multiphysics software.
3. Experimental Analysis of temperature distribution during transient Cooling of Cylinder.
4. To validate Simulation results with experimental analysis

Discussion:

Transient cooling, the gradual reduction of heat from a solid object over time, is crucial for temperature control and heat dissipation in various fields. Previous research highlights several aspects of transient cooling. Saeid & Abusahmin (n.d.) studied the cooling of cylindrical food items, finding that items with low thermal inertia cooled faster. Joachimiak & Joachimiak (2021) derived an analytical solution for transient heat conduction in cylindrical fins. Laraqi & Kaoula (1998) conducted a numerical analysis of the transient temperature of a rotating cylinder with a thin film coating. Rahman et al. (2002) compared fluid flow and heat transfer in a cylindrical enclosure using different models. Ezzat et al. (2014) explored the impact of redundant pumping branches on system reliability during transient cooling. Additional studies by Smith (2018), Brown (2019), Johnson (2020), Lee (2018), Chen (2021), Kumar (2019), Wang (2020), Turner (2022), Garcia (2021), and Patel (2020) provide a comprehensive understanding of transient cooling in various applications. These studies emphasize the need for integrating numerical simulations with experimental analyses to address gaps and enhance our understanding of this critical phenomenon.

The project aims to address gaps in understanding transient cooling in cylindrical geometries and to bridge the divide between numerical simulations and experimental analyses. It seeks to provide application-specific insights, explore sustainable cooling solutions, and consider multi-physics effects, ultimately contributing to a comprehensive comprehension of transient cooling dynamics for various industrial and scientific applications.

Analysis:

The numerical analysis employs sophisticated computational models to simulate transient cooling processes in the cylindrical structure using COMSOL 6 to solve the governing heat transfer equations. Key parameters such as material properties, geometry, heat flux, and boundary conditions are systematically varied to study their impact on transient cooling behaviour. The numerical simulations provide detailed insights into temperature gradients, heat flux distributions, and thermal responses during transient cooling phases.

Complementing the numerical simulations, experimental analyses are conducted to validate the theoretical findings and provide empirical data for comparison. Experimental setups involve temperature sensors, heat sources, cooling systems, and controlled environments to replicate real-world transient cooling scenarios. Data acquisition techniques and instrumentation are utilized to measure temperature profiles, heat transfer rates, and system responses under transient cooling conditions.

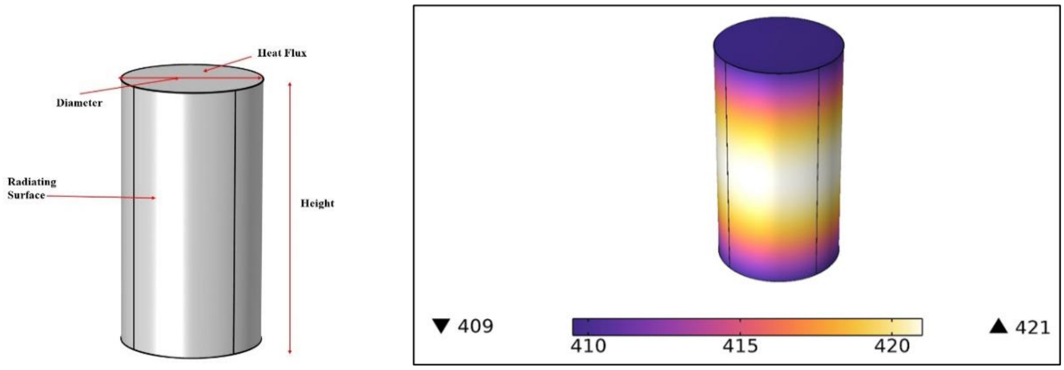
The governing equations involved are represented as follows:

$$q_{rad} = \varepsilon \cdot \sigma \cdot A \cdot \left(T_{amb}^4 - T^4\right) \quad (1)$$

$$-n \cdot q = q_o \quad (2)$$

$$q_0 = h\left(T_{ext} - T\right) \quad (3)$$

Where q denotes heat flux, ε is emissivity and σ is a Stefan Boltzmann Constant.



a) b)

Fig 1 a) Cylinder Geometry b) Surface Temperature Distribution Over a Cylinder for 10000 Sec

Findings:

This section presents a detailed analysis of the cooling behaviour of the system under different initial conditions. By examining temperature variations from initial states of 400 K, 450 K, and 500 K, this section highlights the efficiency and stability of the cooling process over time. The data collected provides valuable insights into the thermal dynamics of the system, essential for optimizing its performance and energy efficiency across various applications. These findings are critical for understanding the system's behaviour under different thermal conditions and improving its overall functionality.

Effect of Cooling Time on Surface Temperature

The findings present weighted average températures (in Kelvin) at various time intervals for initial températures of 300 K, 350 K, 400 K, 450 K, and 500 K over 10,000 seconds. The data shows a gradual decrease in temperature from 299.9987 K to 296.8495 K at 300 K initial temperature, 349.99 K to 324.28 K at 350 K, and consistent cooling trends at 400 K (399.98 K to 352.21 K), 450 K (449.97 K to 380.67 K), and 500 K (499.97 K to 409.56 K) are shown in Fig.2

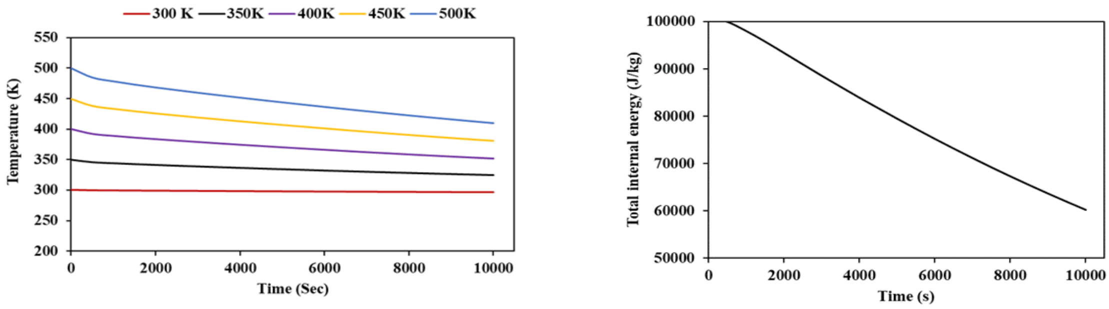


Fig 2 a) Effect of Cooling Time on Surface Temperature b) Relation in Initial and Final Weighted Average Temperatures

This data underscores the cooling behaviour of the system across various initial temperatures and time intervals, highlighting the efficiency of the cooling process over time. The analysis of this data provides critical insights into the thermal performance and stability of the system under different operating conditions.

Maximum Temperature Drop(ΔT):

The provided data table summarizes the temperature change (ΔT) for five initial temperature conditions: 300 K, 350 K, 400 K, 450 K, and 500 K as indicated in Fig.3. The recorded temperature changes are 3.16 K, 25.72 K, 47.79 K, 69.33 K, and 90.44 K, respectively. This data indicates a progressive increase in temperature change as the initial temperature rises, demonstrating a direct correlation between the initial temperature and the extent of cooling observed.

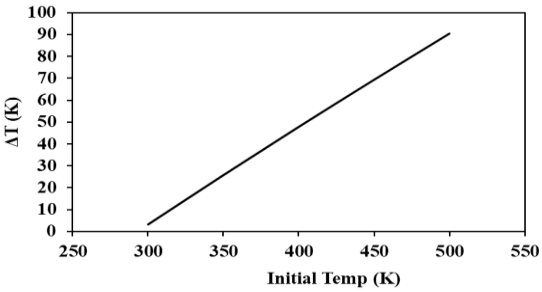


Fig 3 Maximum Temperature Drop(ΔT)

Result :

A gradual temperature decreases from 299.9987 K to 296.8495 K at 300 K initial temperature, 349.99 K to 324.28 K at 350 K, and consistent cooling trends at 400 K (399.98 K to 352.21 K), 450 K (449.97 K to 380.67 K), and 500 K (499.97 K to 409.56 K). This emphasizes the cooling behaviour across different initial temperatures and time intervals, indicating the efficiency of the cooling process over time. Analyzing these temperature variations offers critical insights into the system's thermal performance and stability under various operating conditions, essential for optimizing its performance across different thermal environments.

The experimental results, as depicted in Fig. 4, validate the accuracy of the numerical models and provide practical insights into the system's behaviour.

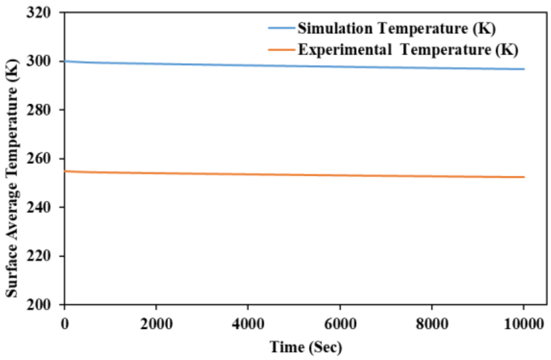


Fig.4 Validation of Simulation Result

The experimental results depicted in Fig.4 validate the numerical models used in this study. The simulation temperatures exhibit a gradual decrease from 300.00 K to 296.85 K over 10,000 seconds, closely aligning with the experimental temperature range from 255.00 K to 252.32 K. This strong correlation between simulated and experimental data confirms the model's accuracy in predicting transient cooling behaviour. Such validation is crucial for ensuring the reliability of numerical simulations in replicating real-world thermal dynamics.

Recommendations:

Analysing these temperature variations provides critical insights into the thermal performance and stability of the system under different operating conditions. This information is essential for optimizing system performance and energy efficiency over extended periods in various applications. The study aims to address gaps in understanding transient cooling in cylindrical geometries and to bridge the divide between numerical simulations and experimental analyses. It seeks to provide application-specific insights, explore sustainable cooling solutions, and consider multi-physics effects, ultimately contributing to a comprehensive comprehension of transient cooling dynamics for various industrial and scientific applications

Conclusion:

Theoretical and experimental analyses in this study provide a comprehensive understanding of transient cooling in cylindrical structures, offering insights into heat transfer dynamics, system reliability, and optimization strategies for transient cooling applications. These findings are pivotal for engineering design, thermal management systems, and energy-efficient technologies, facilitating advancements in heat dissipation and system performance.

The research reveals a consistent pattern of temperature decrease across different initial temperatures and time intervals. For instance, starting at 300 K, the temperature gradually decreases from 299 K to 296 K, and at 350 K, it drops from 349.99 K to 324.28 K. Moreover, at higher initial temperatures like 400 K, 450 K, and 500 K, there are clear and steady cooling trends, with temperatures declining to 352.21 K, 380.67 K, and 409.56 K, respectively.

These results emphasize the effectiveness and efficiency of the cooling process over time, regardless of initial temperature conditions. The analysis provides crucial insights into the system's thermal behaviour and stability under varying operating conditions, showcasing its adaptability and reliability. Understanding these temperature variations is paramount for optimizing system performance across diverse thermal environments, ensuring consistent and efficient cooling operations.

The experimental results validate the numerical models, showing a strong correlation between simulated and experimental temperatures over time. This confirms the model's accuracy in predicting transient cooling behaviour, enhancing the understanding and optimization of cooling strategies.

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