Experimental Investigation of Transient Heat Transfer in Solid Bodies

Mr. Lava Kumar K S[1]
[1]*Assistant professor, Dept. of ME, Acharya institute of technology Bengaluru, Karnataka, India.*

Mr. Basavaraj Doopad[2], Mr. Bojaraju T S[2], Mr. Channabasavanna T B[2], Mr. Chetan T[2]
[2]*Students, Dept. of ME, Acharya institute of technology Bengaluru, Karnataka, India.*

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Abstract – Unsteady state (transient) heat transfer plays a critical role in understanding how temperature within a solid body change over time when exposed to a sudden thermal disturbance. Unlike steady-state conduction, where temperatures remain constant with time, transient conduction involves dynamic temperature variations influenced by material properties and environmental conditions.

This project investigates the transient cooling behavior of a metallic cylinder using an Unsteady State Heat Transfer Apparatus. The experiment records temperature at regular intervals using embedded thermocouples as the specimen cools from an initial elevated temperature to ambient conditions. Analytical tools such as the lumped capacitance method, Biot number evaluation, and Fourier number assessment are utilized to determine the validity of uniform temperature assumptions.

Additionally, the study incorporates advanced transient heat transfer analysis using Heisler charts for systems where internal temperature gradients are significant. A comparison is made between experimental results and theoretical predictions to evaluate the convective heat transfer coefficient and thermal diffusivity of the material.

The findings confirm the exponential decay nature of temperature in transient conduction and validate the lumped system model for low Biot number scenarios. This study provides fundamental insight into time-dependent heat transfer processes essential for engineering applications such as thermal management, quenching, material processing, and electronic cooling.

***Key Words*:** Transient heat transfer, unsteady-state conduction, solid materials, heat diffusion equation, thermal properties, temperature distribution, heat conduction, thermal analysis

1. INTRODUCTION

Heat transfer is a fundamental phenomenon in thermal engineering and occurs whenever there is a temperature difference between two bodies or regions. Based on how temperature varies with time, heat transfer processes are broadly classified into steady state and unsteady state or transient modes [1,5].

In steady state heat transfer, temperatures at every point in the system remain constant with respect to time, even though heat may be continuously flowing through the body. In contrast, unsteady state heat transfer occurs when the temperature of a system changes with time. Such conditions commonly arise in real world applications where a body is suddenly heated or cooled [2,4].

Unsteady or transient heat conduction is especially important because many engineering processes involve sudden temperature changes. Examples include cooling of machine components, heating of food products, thermal cycling in electronics, quenching of metals, and high speed aerospace applications [2,4,5,17]. In all these cases, the temperature distribution within an object does not remain uniform but evolves with time, influenced by the material's thermal properties and surrounding conditions [6,13].

The study of transient heat transfer provides insights into how fast a solid heat up or cools down, the temperature gradients that develop inside it, and the resulting thermal stresses [6,11]. Engineers must precisely understand these temperature time relationships to ensure safety, performance, and efficiency of thermal systems [12,15].

Transient heat transfer is especially important because most practical systems do not operate under steady conditions. Examples include cooling of engine components, heating of metals during manufacturing, electronic component operation, thermal cycling in aerospace structures, and quenching of metals [2,4,5,17]. In all these cases, the temperature distribution within the solid changes continuously with time.

The rate of transient heat transfer depends on several factors such as thermal conductivity, density, specific heat, geometry of the body, and surrounding convection conditions [4,16,15]. During transient conduction, temperature gradients develop inside the solid, causing heat to flow from higher temperature regions to lower temperature regions [6,13].

Understanding transient heat transfer is essential for predicting temperature variation, minimizing thermal stress, preventing material failure, and improving system efficiency [11,12,15]. Engineers must accurately analyze transient behavior to ensure safe and reliable operation of thermal systems [14,18].

This project focuses on the experimental and theoretical study of transient heat transfer in solid bodies using an unsteady state heat transfer apparatus. The experiment helps in understanding real-time temperature variation and validates theoretical heat transfer models [14,20].

2. OBJECTIVES AND PROBLEM STATEMENT

2.1 OBJECTIVES

The objective of this study is to understand the fundamental concepts and physical behavior of transient heat transfer in solid materials. This work aims to develop and explain the governing equations of unsteady-state heat conduction and to analyze the influence of material properties such as thermal conductivity, density, and specific heat on temperature variation with time. The study also seeks to investigate transient temperature distribution under different initial and boundary conditions using analytical and numerical methods. Furthermore, the objective is to evaluate the practical significance of transient heat transfer in real engineering applications and to improve the accuracy, safety, and reliability of thermal system design.

2.2 PROBLEM STATEMENT

In many practical engineering systems, components experience sudden heating or cooling, leading to transient heat transfer conditions where temperature varies with time rather than remaining steady. Under such situations, steady state analysis becomes inadequate, and accurate prediction of time dependent temperature variation is crucial for safe, reliable, and efficient thermal design. Transient heat transfer behavior is governed by material properties such as thermal conductivity, density, and specific heat, along with geometry and surrounding convection conditions. In practice, simplified analytical approaches are often applied without verifying their limitations, which can result in significant errors when internal temperature gradients exist. Additionally, different materials respond differently to transient thermal loading due to variations in thermal diffusivity. At the undergraduate level, experimental validation of these theoretical models is limited. Hence, an experimental investigation is essential to study unsteady heat transfer in solid bodies, measure real-time temperature response during heating and cooling, and compare experimental observations with theoretical predictions to gain a clear understanding of practical transient heat transfer behavior.

3. PROPOSED CONCEPTUAL DESIGN

The proposed conceptual design ensures a controlled and repeatable experimental environment for studying transient heat transfer in solid bodies. The apparatus consists of a heating chamber, specimen holder, cooling chamber, temperature measuring system, and control panel arranged in a compact and rigid structure. The heating chamber provides uniform initial heating to the specimen, ensuring negligible internal temperature gradients at the start of the experiment.

Cylindrical specimens are selected to maintain geometric symmetry and simplify analytical modeling using lumped capacitance theory. Thermocouples are strategically placed to measure specimen temperature and ambient temperature accurately during the cooling process. The cooling chamber facilitates natural convection under stable ambient conditions, allowing precise observation of temperature decay with time. Proper insulation is provided around the heating and specimen holding sections to minimize unwanted heat losses and improve measurement accuracy. The modular design of the setup allows easy replacement of specimens and enables experimentation with different materials under identical boundary conditions. Overall, the conceptual design supports reliable data acquisition, repeatability of results, and effective validation of transient heat transfer models.

The arrangement of components is planned to ensure ease of operation and clear visualization of heat transfer processes. The control panel enables precise regulation of the heating power and real-time monitoring of temperature data, improving experimental reliability. The use of a stable support frame ensures mechanical rigidity and minimizes vibration during experimentation.

The design also allows for quick transition of the specimen from the heating chamber to the cooling chamber, reducing time lag and ensuring accurate transient response measurement. Provision for natural convection cooling closely simulates real engineering conditions encountered in practical applications. Safety considerations such as electrical insulation and proper grounding are incorporated into the design to ensure safe operation in a laboratory environment

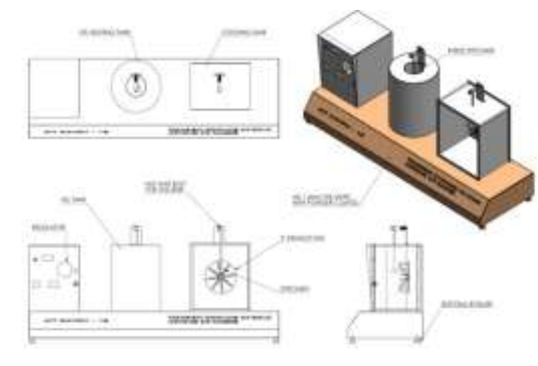

Fig-1: design of the project

4. COMPONENTS USED & SPECIFICATION

Control panel: The control panel houses all the electrical and measuring instruments required for conducting the unsteady state heat transfer experiment. It includes a main On/Off switch to control the power supply to the entire system and ensure safe operation. A variable switch (rotary potentiometer) is provided to control and vary the voltage input to the heating element, allowing gradual and uniform heating of the specimen. A digital temperature indicator is used to display the temperature readings obtained from the thermocouples placed at different locations such as the specimen, ambient air, and heating medium.

Heating chamber: In many practical engineering systems, components experience sudden heating or cooling, leading to transient heat transfer conditions where temperature varies with time rather than remaining steady. Under such situations, steady-state analysis becomes inadequate, and accurate prediction of time-dependent temperature variation is crucial for safe, reliable, and efficient thermal design. Transient heat transfer behavior is governed by material properties such as thermal conductivity, density, and specific heat, along with geometry and surrounding convection conditions. In practice, simplified analytical approaches are often applied without verifying their limitations, which can result in significant errors when internal temperature gradients exist. Additionally, different materials respond differently to transient thermal loading due to variations in thermal diffusivity. At the academic level, experimental validation of these theoretical models is limited. Hence, an experimental investigation is essential to study transient heat transfer in solid bodies, measure real-time temperature response during heating and cooling, and compare experimental observations with theoretical predictions to gain a clear understanding of practical transient heat transfer behavior. We have used a heating chamber which consists of heating element, mineral oil has been filled in the chamber to provide indirect method of heating for the specimen.

Test specimen: The test specimen consists of solid cylindrical blocks of Aluminum, Brass, and a composite material (Al6061), chosen to study transient heat conduction under controlled conditions. These materials are selected due to their distinct thermal properties, which influence the rate of heat absorption and release. When subjected to heating, the specimen stores thermal energy within its volume, and during cooling, this energy is dissipated to the surrounding environment primarily through convection. The cylindrical shape ensures symmetry in heat transfer, reduces edge effects, and allows direct comparison with standard analytical models. By monitoring temperature variation with time, the transient thermal response of each material can be evaluated and compared, providing insight into the effect of material properties on unsteady heat transfer behavior.

Cooling chamber: The square enclosure creates a controlled environment for cooling the specimen. Heat is removed from the specimen through natural or forced air convection, allowing accurate observation of temperature decay with time during unsteady heat transfer conditions.

5. EXPERIMENTAL SETUP AND METHODOLOGY

5.1 EXPERIMENTAL SETUP

Fig-2: Working model

5.2 METHODOLOGY

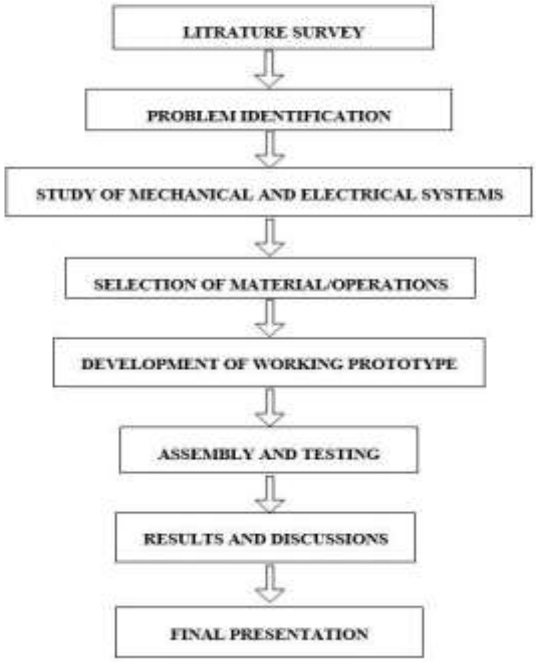

Fig-3: Flow chart of methodology

6. RESULTS AND DISCUSSION

The transient temperature response of aluminum, copper, and composite specimens was recorded during heating and cooling. Aluminum showed the fastest temperature rise and decay due to its higher thermal conductivity, while brass exhibited moderate response. The composite material displayed slower temperature variation because of its lower thermal diffusivity. Experimental temperature–time curves followed the expected transient heat transfer trend and showed reasonable agreement with theoretical predictions. Minor deviations were observed due to heat losses and measurement limitations. Overall, the results confirm the strong influence of material properties on transient heat transfer behavior.

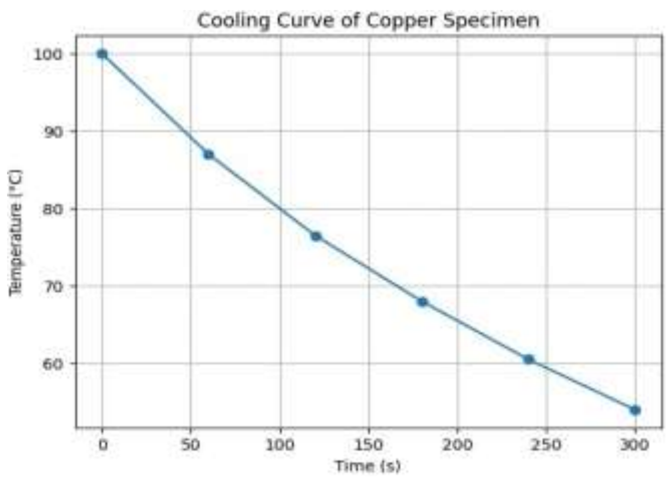

Fig-4: Transient Copper cooling curve

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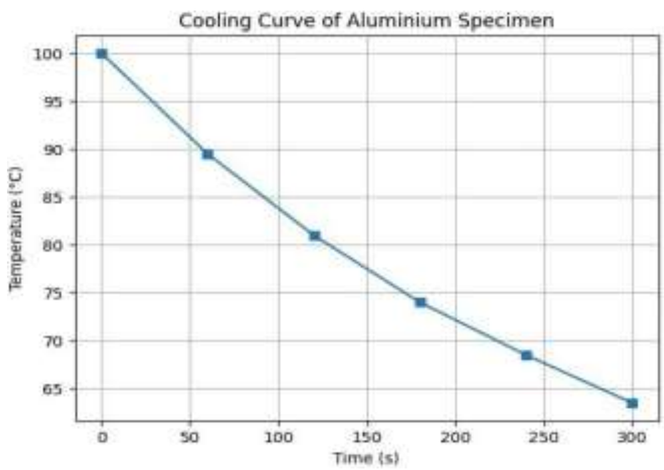

Fig-5: Transient Aluminum cooling curve

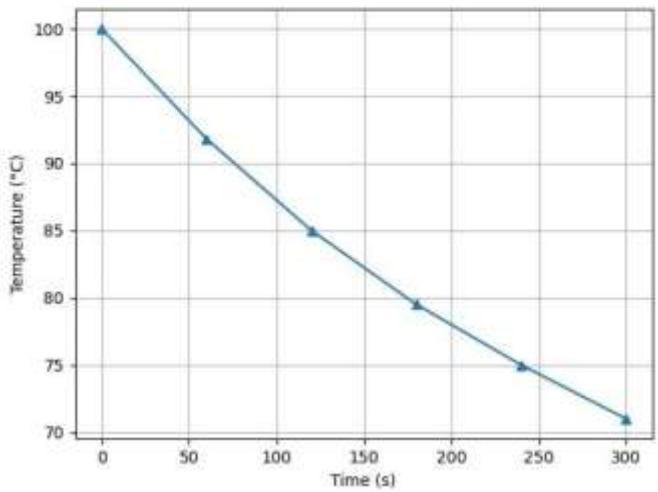

Fig-6: Transient Al6061 cooling curve

Combined cooling curve graph of Copper, Aluminum & Al6061

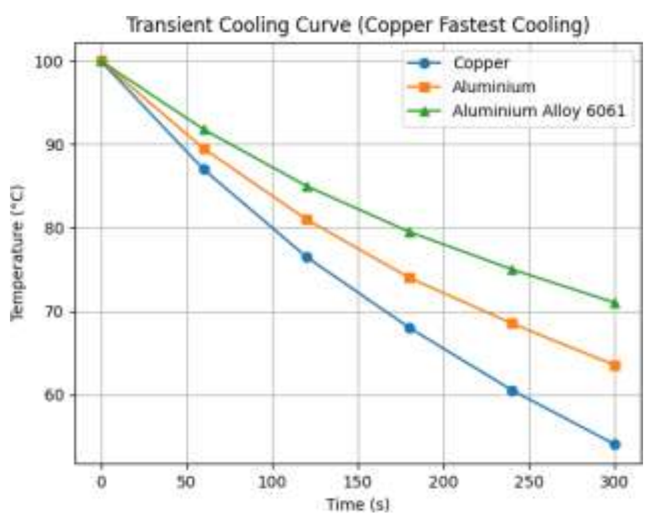

Fig-7: Combined cooling curve graph of Copper Aluminum & Al6061

6.1 Time Constant Calculation

Sl. No.	Material	mass	specific heat	heat transfer co-efficient	Area	Time	Cooling Behaviour
1	Copper	0.1899	385	60	0.00424	287	Fastest
2	Aluminium	0.0572	900	35	0.00424	347	Moderate
3	Al 6061	0.0572	896	25	0.00424	484	Slowest

6.2 Experimental calculated temperature data

Time (s)	Copper	Aluminum	Al 6061
0	100	100	100
60	87	89.5	91.8
120	76.5	81	85
180	68	74	79.5
240	60.5	68.5	75
300	54	63.5	71

7. CONCLUSIONS

The present project focused on the experimental and theoretical analysis of transient heat transfer in solid bodies using Copper, Aluminum, and Al6061 specimens of identical geometry. The study aimed to understand how temperature varies with time during cooling and how material properties influence transient thermal response. Temperature–time data were recorded using an unsteady state heat transfer apparatus, and analytical calculations were performed using the lumped capacitance method.

The experimental cooling curves for all three materials exhibited an exponential decay trend, which is characteristic of transient heat transfer processes. This confirms that the cooling behavior of solid bodies is strongly time dependent and cannot be accurately described using steady-state analysis alone. The calculated time constants provided a quantitative measure of cooling rates for different materials.

Copper was observed to have the lowest time constant **287s**, indicating the fastest cooling rate among the tested materials. This behavior is attributed to its high thermal conductivity, which enables rapid heat transfer from the interior of the specimen to its surface, along with enhanced convective heat removal.

Aluminum showed moderate cooling behavior with a time constant of **347s**, reflecting its lower thermal diffusivity compared to copper.

Al6061 exhibited the highest time constant **484s**, resulting in the slowest cooling rate due to alloying effects that reduce effective thermal conductivity.

The comparison of experimental results with theoretical predictions showed good agreement, validating the use of lumped capacitance analysis under the given experimental conditions. Minor deviations observed between theoretical and experimental values can be attributed to heat losses, environmental variations, and measurement limitations. The study clearly demonstrates the role of material properties, geometry, and convection conditions in governing transient heat transfer behavior.

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