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*Article*

# Investigation of the mechanical equivalent of heat using aluminum and brass cylinders

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**Abstract.** This study explores the mechanical equivalent of heat through controlled experiments using aluminum and brass cylinders. By mechanically rotating these cylinders against a friction band, the conversion of mechanical energy into heat is quantified, demonstrating a fundamental thermodynamic process. The experiment is designed to calculate the specific thermal capacities of the metals and evaluate the efficiency of energy transformation. Results validate the concept that mechanical energy, when converted through friction, becomes thermal energy—affirming the principles outlined in the conservation of energy. This research not only reinforces classical thermodynamics but also enhances our understanding of material properties under thermal stress, offering insights applicable to industrial applications and renewable energy technology. The findings underscore the practical implications of energy transformations in material science and engineering, contributing to the development of more efficient thermal management systems in various technological fields.
**Keywords:** mechanical equivalent of heat, thermodynamics, energy transformation, aluminum, brass, renewable energy.

## 1. Introduction

Understanding thermal properties such as thermal diffusivity and heat transfer coefficients is crucial in various fields, including materials science, engineering, and applied physics [1]. These properties play a vital role in designing and optimizing systems and processes that require efficient thermal management. From improving the performance of electronic devices by enhancing heat dissipation to designing more efficient heat exchangers and optimizing industrial cooling processes, the accurate assessment of these thermal properties can lead to significant advancements in technology and energy efficiency [1], [2].

Thermal diffusivity is a measure of how quickly a material can conduct heat relative to its ability to store thermal energy. This property is essential for materials used in applications where they are subjected to rapid temperature changes. Materials with high thermal diffusivity can quickly adapt their temperature to match their surroundings, which is critical in applications [3]. For instance, the design of spacecraft materials that can withstand extreme temperature fluctuations during entry and exit from planetary atmospheres depends heavily on materials with optimal thermal diffusivity [4], [5].

Similarly, the heat transfer coefficient is a measure that describes the heat transfer between a solid surface and a fluid per unit area per unit temperature difference [6]. This coefficient is foundational for the design and analysis of equipment such as radiators, boilers, and heat exchangers. It determines how effectively a material can transfer heat to its environment or between materials, impacting everything from industrial processing equipment to household heating systems [7].

The practical importance of these thermal properties can be seen in a wide range of applications. In the electronics industry, for example, managing the heat produced by devices is critical to maintaining functionality and longevity [8]. Thermal management solutions, which are based on understanding thermal diffusivity and heat transfer coefficients, are essential for preventing overheating and ensuring that devices operate within safe temperature limits. Similarly, in the construction industry, materials with tailored thermal properties are used to enhance energy efficiency in buildings through better insulation and heat management [9].

Furthermore, in the energy sector, efficient thermal management is key to improving the performance of systems like solar panels and nuclear reactors [10], [11]. For solar panels, materials that can dissipate heat effectively lead to higher efficiency and longer panel lifespans. In nuclear reactors, managing the heat generated during fission processes is critical for safety and efficiency, underscoring the importance of materials with precise thermal properties. Theoretical models and experimental methods have been developed to measure these properties accurately. These models often involve complex calculations that consider the unique conditions and constraints of specific applications. Experimentally, techniques such as laser flash analysis for thermal diffusivity and guarded hot plate methods for thermal conductivity measurement are commonly used. These methods provide the data necessary to simulate real-world conditions and predict how materials will behave in specific thermal environments.

Advancements in computational tools have also enhanced our ability to analyze and predict the behavior of materials under various thermal conditions. Simulation software can model heat transfer in complex systems, allowing engineers and scientists to visualize and optimize setups before physical prototypes are built. This not only saves time and resources but also allows for more creative solutions to thermal management challenges [12], [13].

As we continue to push the boundaries of what is technologically possible, the study of thermal properties becomes even more significant. Innovations in materials science, bolstered by a deeper understanding of thermal diffusivity and heat transfer, are leading to the development of materials that perform better, last longer, and are safer than ever before. This progress is essential as we tackle the challenges of energy efficiency, electronic device miniaturization, and environmental sustainability. Thus, thermal diffusivity and heat transfer coefficients are critical factors that influence the design and functionality of numerous systems across a variety of industries. Understanding these properties in detail enables the development of better materials and systems that meet the increasing demands of modern applications, driving forward innovations in technology and industrial processes.

## 2. Methods

The study's primary objective was to determine the thermal diffusivity and heat transfer coefficients of aluminum and brass across three geometric configurations: slabs, cylinders, and spheres. To achieve this, a comprehensive experimental setup was developed, consisting of temperature-controlled environments for both water and air mediums.

The experimental apparatus included a thermally insulated chamber for air experiments and a water bath for aquatic experiments, both equipped with precision heating elements to maintain target temperatures of 25°C for air and 52°C for water. Aluminum and brass samples were machined into the specified geometric shapes, each measured for uniformity and surface finish to ensure consistency in thermal contact and boundary conditions.

Each sample was embedded with type E thermocouples at strategic locations to record temperature data. These thermocouples were connected to a digital data logger that captured temperature readings at pre-defined intervals. This setup allowed for the continuous monitoring of temperature changes as the samples reached thermal equilibrium with their environments.

To initiate the experiments, each sample was first brought to a stabilized temperature condition. For water experiments, the samples were submerged in a pre-heated water bath agitated by an external circulation system to minimize thermal layering. In air experiments, samples were placed in the insulated chamber with a controlled airflow to simulate a mild convective environment.

Parallel to the experimental measurements, the finite integral transform (FIT) was employed analytically to solve the heat conduction equations for each geometry. This method involves transforming the spatial domain heat conduction problems into a simpler form, which can be solved using boundary conditions relevant to the experimental setup.

The general heat conduction equation for a homogeneous material is given by:

$$\frac{\partial}{\partial \mathrm{x}}\left(k\frac{\partial \mathrm{T}}{\partial \mathrm{x}}\right) = pc_p\frac{\partial \mathrm{T}}{\partial \mathrm{t}} \tag{1}$$

where $T$ is the temperature, $k$ is the thermal conductivity, ρ is the density, and $c_p$ is the specific heat capacity of the material. For each of the shapes (slab, cylinder, sphere), the equation was tailored to account for the specific geometry and boundary conditions observed during the experiments (Figure 1).

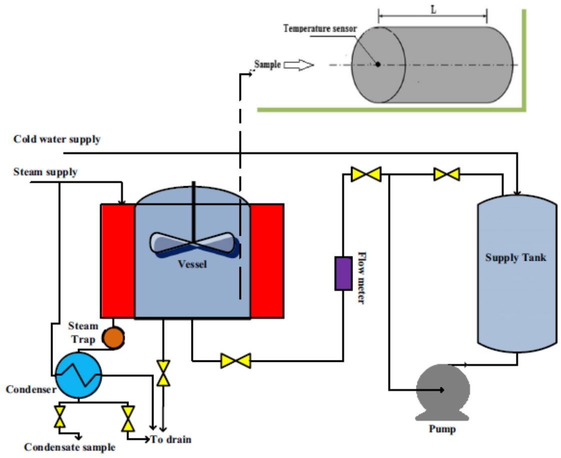


Figure 1 – Experimental equipment

Using the FIT, these equations were transformed into their respective eigenvalue problems, which could be solved to find the temperature distribution as a function of time and space. The solutions provided a theoretical prediction of how temperature should change in each sample under ideal conditions. The analytical results from FIT were then compared to the experimental data. The comparison involved calculating the root mean square error between the predicted and observed temperatures to evaluate the accuracy of the FIT method in predicting the thermal behavior of the materials under study.

## 3. Results and Discussion

Neglected were the thermal capabilities of the heat-conductive paste and the insulated bearing. A temperature-time curve is shown as an example of measurement in Fig. 3. The graph's structure makes it evident that as the crank is being spun, thermal energy is continuously released into the atmosphere. Therefore, temperature differential T is calculated using the same method as specific heat, which involves extending both straight graph branches to account for transient temperature compensation. The temperature difference T sought after is equal to the difference of the ordinates of the points of intersection of two straight lines drawn parallel to the temperature axis so as to generate two equal surfaces.

Convection is the principal source of cooling for the cylinder. Newton's rule of cooling, which states that "the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings," can be used as a good estimate in this situation.

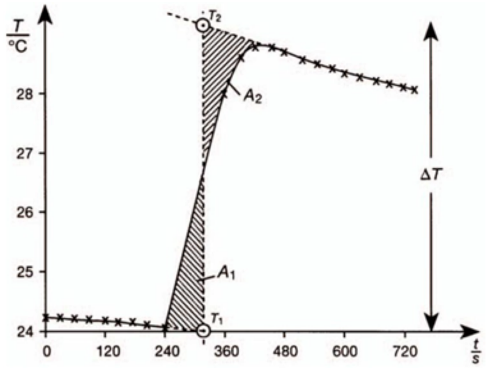


Figure 3 – Diagram showing temperature and time for a measurement example

The temperature difference in Figure 3 approximates the heat loss rate, which is the first derivative of the total amount of heat. As a result, the region restricted beneath the temperature curve in Figure 3 can be graphically represented as the integral of temperature difference equal to the entire quantity of heat lost. Fig. 3 contains two curves. The first one (the actual experiment) relates to the gradual conversion of mechanical work into heat. Instantaneous transfer is demonstrated by the second curve, which is an imagined experiment.

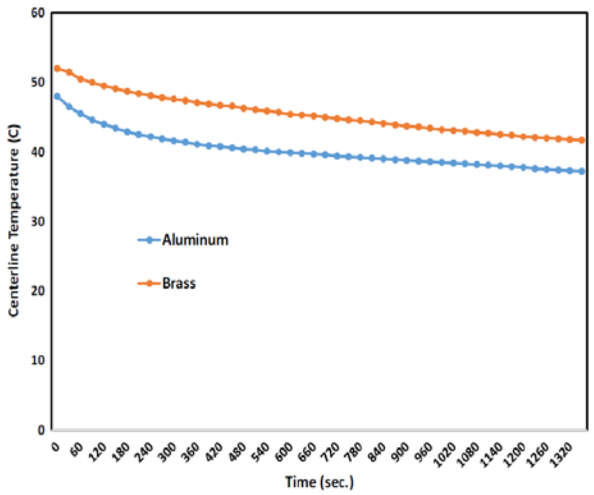


Figure 4 – Temperature ratio at the centerline of a cylindrical object at 52 °C in the atmosphere

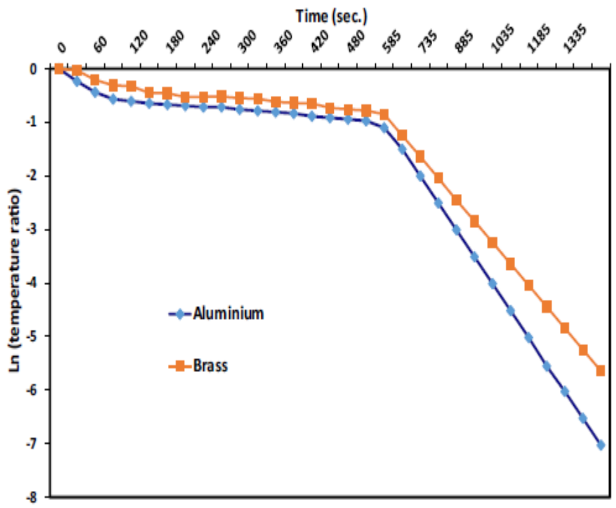


Figure 5 – Temperature differential along the midline of a cylindrical object in 52 °C water

The cylinder in both trials has the same amount of heat both before and after friction-induced heating. For both curves, the mechanical labor is the same. Therefore, for both curves, the area under the curves (the amount of heat lost owing to convection) must be equal. This is only feasible if, which specifically specifies the vertical line's (instantaneous process') location in Figure 3.

For brief time intervals, straight lines can be used to represent the exponential cooling process. After 200 rotations of the friction cylinder, the work equals W = 1301 in the measurement example where the residual load on the dynamometer is = 3 N. Equation (1) states that the friction cylinder's subsequent temperature rise of T = 5.1 K results in the production of Q = 1296 thermal energy. Within the bounds of measurement error, the quotient (1.003) equals 1 if the mechanical heat equivalent is computed. The law of conservation of energy states that as heat is a type of energy, the entire quantity of mechanical energy must be converted into an equal amount of heat energy.

Similarly, investigations involving the conversion of electric energy to thermal energy demonstrate that the comparable electric equivalent of heat W/Q likewise equals to 1. Consequently, the mechanical equivalent of heat must actually equal: 1. The first law of thermodynamics provides a thorough summary of these findings.

Table 1 – Heat transfer coefficient calculations for aluminum and brass in air and water for a cylinder

| No | Material type | Environment | Estimated thermal diffusivity (m2/S) | Calculated heat transfer coefficient | The heat transfer coefficient by literature | Standard deviation | Relative Std. deviation (%) |
|---|---|---|---|---|---|---|---|
| 1 | Al | air | $8.371\times 10^{-5}$ | 1.49 | 1-4 | 0.0000012 | 0.36 |
| 2 | Al | water | - | 33 | | 0.0000371 | 0.54 |
| 3 | Brass | air | $3.401 \times 10^{-5}$ | 2.38 | 1-4 | 0.0000014 | 0.47 |
| 4 | Brass | water | - | 35 | | 0.0000319 | 0.62 |

Table 2 – Heat transfer coefficient calculations for aluminum and brass in air and water for a round shape

| No | Material type | Environment | Calculated heat transfer coefficient | The heat transfer coefficient by literature | Standard deviation | Relative Std. deviation (%) |
|---|---|---|---|---|---|---|
| 1 | Al | air | 1.49 | - | 0.0000014 | 0.38 |
| 2 | Al | water | 33.4 | - | 0.0000411 | 0.62 |
| 3 | Brass | air | 2.37 | - | 0.0000014 | 0.47 |
| 4 | Brass | water | 34.6 | - | 0.0000317 | 0.61 |

The centerline temperature variations for each of the three standard geometric shapes—an infinite slab 50 mm thick, an infinite cylinder 50 mm diameter, and a spherical object 50 mm diameter—were carefully documented in order to evaluate the thermal diffusivity and heat transfer coefficient of each shape. Brass and aluminum were used in the experiments, which were carried out in two different temperatures: an air medium at 25 °C and a water medium with strong stirring. The temperature ratio changes at the centerline of these geometries in the water medium are shown in Figures 3, 5, and 7, while the changes in the air medium are shown in Figures 4, 6, and 8. Table 1-2 lists the thermal diffusivities for brass and aluminum for spherical and cylindrical geometries. Brass and aluminum have reported thermal diffusivities of $3.401 \times 10^{-5}$ m³/s and $8.371 \times 10^{-5}$, respectively, with relative errors also listed in Table 1-2. The thermal diffusivity of brass and aluminum has Total Average Absolute Deviation values of 0.39 and 0.42, respectively.

## 4. Conclusions

The most crucial thermophysical material metrics for characterizing a material's or component's heat transport characteristics are thermal conductivity and diffusivity. Thermal conductivity can be measured using a variety of techniques, each of which is only appropriate for a specific class of materials based on the thermal characteristics and the ambient temperature. There are two categories of techniques for determining a sample's thermal conductivity: steady-state techniques and nonsteady-state techniques. A detailed explanation of the various methods used to determine thermal conductivity and thermal diffusivity through experimentation was provided. Since the experimental data from the fascinating material is needed for these methods with analytical solutions.

When compared to more popular approaches, such the lumped system approach or the use of empirical equations to calculate these heat transfer parameters, these methods offer a bigger advantage. These methods demonstrate how one parameter must be known in order to determine the other (for example, thermal conductivity must be known in order to determine the thermal diffusivity value). As a result, creating or improving a process to ascertain both factors at the same time is still crucial. Heat transfer parameters can be found using the experimental data and the Finite Integral Transform method (for a solution of the governing differential equation).

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