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IMPLEMENTATION OF NATURAL COOLING IN INDUSTRIAL MACHINERY TO SUPPORT GREEN INDUSTRY THROUGH ENERGY CONSERVATION

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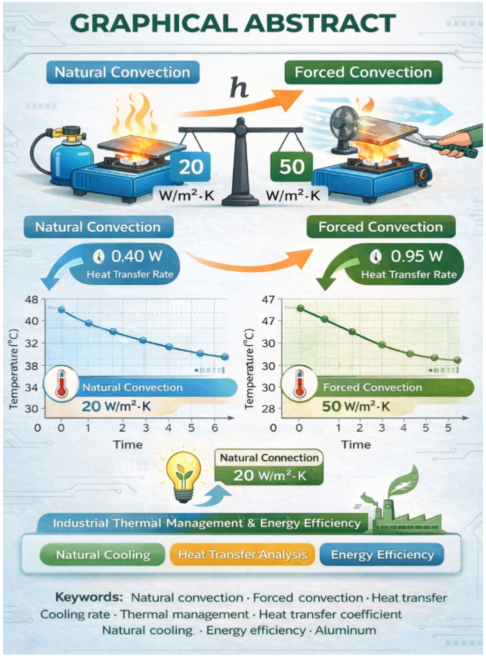
Graphical Abstract



Abstract

Overheating reduces the reliability and performance of industrial machinery by increasing wear, maintenance costs, and downtime. Effective thermal management is therefore essential to maintain system performance and extend equipment life. This study analyzes heat transfer through natural and forced convection on a flat aluminum plate and evaluates their effectiveness in heat dissipation. A quantitative experimental method was used to compare temperature changes under two conditions: natural convection and forced convection with fan-assisted airflow. The experiment was conducted by heating an aluminum plate and measuring its surface temperature at 1-minute intervals for 5 minutes. The collected data were used to determine the convective heat transfer coefficient (h) and the rate of heat transfer (q) based on Newton's Law of Cooling. The results show that forced convection provides a higher heat transfer coefficient (50 W/m²·K) than natural convection (20 W/m²·K), resulting in a faster decrease in temperature. The maximum heat transfer rate was observed at the initial time, reaching 0.95 W for forced convection and 0.40 W for natural convection, with both values decreasing over time as the temperature difference diminished. These findings confirm that airflow significantly enhances heat transfer performance by increasing the convective coefficient by up to twofold. However, natural convection remains a viable passive cooling method due to its energy efficiency, as it requires no additional energy input. With proper design optimization, natural cooling systems can be equivalent to forced-convection systems and contribute to sustainable, energy-efficient thermal management solutions.

Keywords: Natural convection; Forced convection; Heat transfer; Cooling rate; Thermal management; Heat transfer coefficient; Natural cooling; Energy efficiency; Green industry; Aluminum plate.

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1. Introduction

Excessive heat in machinery (overheating) is a critical factor that can reduce the reliability of mechanical systems. This condition not only degrades operational performance but also accelerates wear and damage to key components[1], such as bearings, lubricants [2], and other structural elements [3]. In an industrial context, machinery represents a vital asset that directly supports the continuity of production processes. Therefore, a decline in machine reliability due to overheating can significantly reduce operational efficiency, increase maintenance costs, and lead to economically detrimental downtime [4][5]. Consequently, controlling the operating temperature of machinery is essential for maintaining system performance and extending equipment service life [6].

Heat dissipation in machinery occurs through heat transfer mechanisms, primarily conduction and convection. Conduction refers to heat transfer through solid materials from regions of higher temperature to lower temperature, while convection involves heat transfer from a solid surface to a surrounding fluid, such as air or a cooling liquid [7] [8]. In practice, various thermal management methods are applied in mechanical systems, including forced convection using fans or pumps and fluid-based cooling systems. However, natural convection is still widely utilized due to its inherent energy efficiency, as it does not require additional energy input during operation [9][10]. Therefore, natural convection represents an economical and energy-efficient alternative, particularly for systems with moderate thermal loads.

The heat dissipation capacity of a system is influenced by several factors, including material properties and surface area. Material properties, particularly thermal conductivity, determine the ability of a material to transfer heat from the source to the surrounding environment [11], [12]. Materials with high thermal conductivity are generally more effective in enhancing heat transfer. In addition, surface area plays a significant role in convective heat transfer, as a larger contact area between the solid surface and the cooling fluid increases the rate of heat dissipation [13][14]. Therefore, optimizing material selection and surface geometry is essential for improving thermal management performance and supporting energy conservation in industrial applications[9].

However, previous studies have predominantly focused on improving heat transfer performance through forced convection methods, with limited consideration of the associated energy consumption [15]. Furthermore, systematic comparisons between natural convection and forced convection under similar operating conditions remain limited, particularly in terms of energy efficiency. Therefore, this study aims to investigate and compare the heat transfer characteristics of natural convection and forced convection on a flat aluminum plate by evaluating the convection heat transfer coefficient and heat transfer rate. The novelty of this research lies in its assessment of natural convection as a potential energy-efficient thermal management strategy, contributing to sustainable engineering practices and energy conservation in industrial systems.

2. Method

2.1. Research Design

This study adopts a quantitative experimental approach to analyze heat transfer under natural and forced convection on a one-dimensional metal plate. The methodology involves a comparative evaluation of the heat transfer characteristics of both convection mechanisms based on experimentally measured temperature data. The experimental design consists of two operating conditions: natural convection and forced convection. In the natural convection condition, heat transfer occurs due to fluid density differences without the assistance of external devices. In contrast, during forced convection, airflow is generated using a fan to enhance the heat transfer rate.

The research procedure comprises two main stages: preparation and experimentation. During the preparation stage, all equipment and materials were assembled, the metal plate was fabricated to the required dimensions, and instrument validation tests were conducted to ensure proper functionality. In the experimental stage, the metal plate was heated to a predetermined temperature, followed by temperature measurements at specified time intervals.

Temperature data were collected at one-minute intervals over a duration of five minutes under two conditions: (i) natural convection (without airflow) and (ii) forced convection (with fan-assisted airflow). The recorded data were subsequently used to determine the convective heat transfer coefficient (h) and the cooling rate of the metal plate. Data analysis was conducted by comparing the convective heat transfer coefficient (h) and the cooling rate obtained under both conditions. Forced convection was considered more effective if it resulted in a higher convective heat transfer coefficient and a faster temperature decay compared to natural convection, while maintaining all other variables constant.

2.2. Experimental Materials and Equipment

The metal plate surface temperature was measured under two heat transfer conditions: natural convection and forced convection. For both conditions, the surface temperature was recorded using an infrared thermometer at 1-minute intervals over a total testing duration of 5 minutes. During the natural convection test, the metal plate was allowed to cool naturally without any externally induced airflow. In contrast, for the forced convection test, airflow was generated using a fan directed toward the metal plate surface. This difference in treatment was intended to observe the influence of convection mechanisms on the plate temperature decay rate**.**

2.3. Research Variables

The independent variable of the study is the convection mechanism, namely natural convection and forced convection. The dependent variables include the metal plate surface temperature as a function of time, the convective heat transfer coefficient (h), and the plate temperature decay rate. Meanwhile, the controlled variables consist of the metal plate material, the dimensions and surface area, the initial temperature, the ambient temperature, the type of working fluid (air), and the measurement time interval (every 1 minute for a total duration of 5 minutes). Additionally, the study assumes steady-state flow conditions and constant thermophysical properties of the fluid throughout the experimental process.

2.4. Experimental Procedure

The research procedure in this study was carried out through two main stages, namely the preparation stage and the experimental stage. Both of which were designed to ensure data accuracy and the consistency of testing conditions. The preparation stage began with assembling all equipment and materials required for the study, including a metal plate, a portable stove, a gas cylinder, and temperature measurement instruments. A flat aluminum plate was then cut to predetermined dimensions to ensure the uniformity of the test specimens. Subsequently, the measuring instruments accuracy, particularly the infrared thermometer, was verified to ensure the temperature data validity and reliability obtained.

Following this, the portable gas cylinder was properly installed on the portable stove in accordance with established safety procedures. Before the experiment begins, a preliminary test of the stove or heating system was conducted to confirm its proper functionality and to ensure a stable flame production. This step was essential to guarantee that the heating process during the experiment would occur under consistent and controlled conditions. The experimental stage begins with igniting the portable stove as the heat source. The flat plate aluminum was securely held using tongs to facilitate handling and to maintain safety during the heating process. The metal plate was then heated over the stove flame until it reached a relatively uniform temperature across its surface. Once sufficient heating was achieved, the plate was removed from the heat source for temperature measurement. Surface temperature measurements were conducted using an infrared thermometer at regular time intervals. This process aimed to observe the temporal variation of the plate's temperature, enabling the analysis of heat transfer characteristics occurring during the cooling process.

2.5. Data Analysis

The measured temperature data were used to determine the heat transfer rate during cooling, assuming that the ambient temperature and the plate material properties remained constant. The convective heat transfer coefficient (h) was calculated at each measurement interval and subsequently averaged to obtain a representative convection coefficient for each heat transfer mechanism.

The effectiveness of natural and forced convection was analyzed by comparing the convective heat transfer coefficient (h) and the plate temperature decay rate over time under both conditions. Forced convection was considered more effective if it produced a higher value of h and a faster rate of temperature reduction than natural convection over the same time interval. This comparison was conducted while maintaining other variables, such as surface area, plate material, initial temperature, and constant ambient conditions, ensuring that any observed differences in results were solely attributable to the convection mechanisms variation.

The convective heat transfer rate is expressed as:

$$q = hA(Ts - T\infty) \qquad (1)$$

Where q is heat transfer rate (W), h is the convective heat transfer coefficient (W/m²·K), A is the plate surface area (m²), Ts is the plate surface temperature (°C), and $T\infty$ is the ambient air temperature (°C).

$$\frac{dT}{dt} = -\boldsymbol{k}\,(\boldsymbol{T} - T_\infty) \qquad (2)$$

Equation (2) represents Newton's Law of Cooling, which states that the temperature decrease rate of an object is proportional to the temperature difference between the object and its surrounding environment. Upon integration, the following expression is obtained:

$$(\boldsymbol{T} - T_\infty) = (\boldsymbol{T_0} - T_\infty)e^{-kt} \qquad (3)$$

In Equation (3), $\boldsymbol{T_0}$ represents the plate initial temperature after heating, T denotes the temperature at time t, T_∞ is the ambient temperature, and k is the cooling constant.

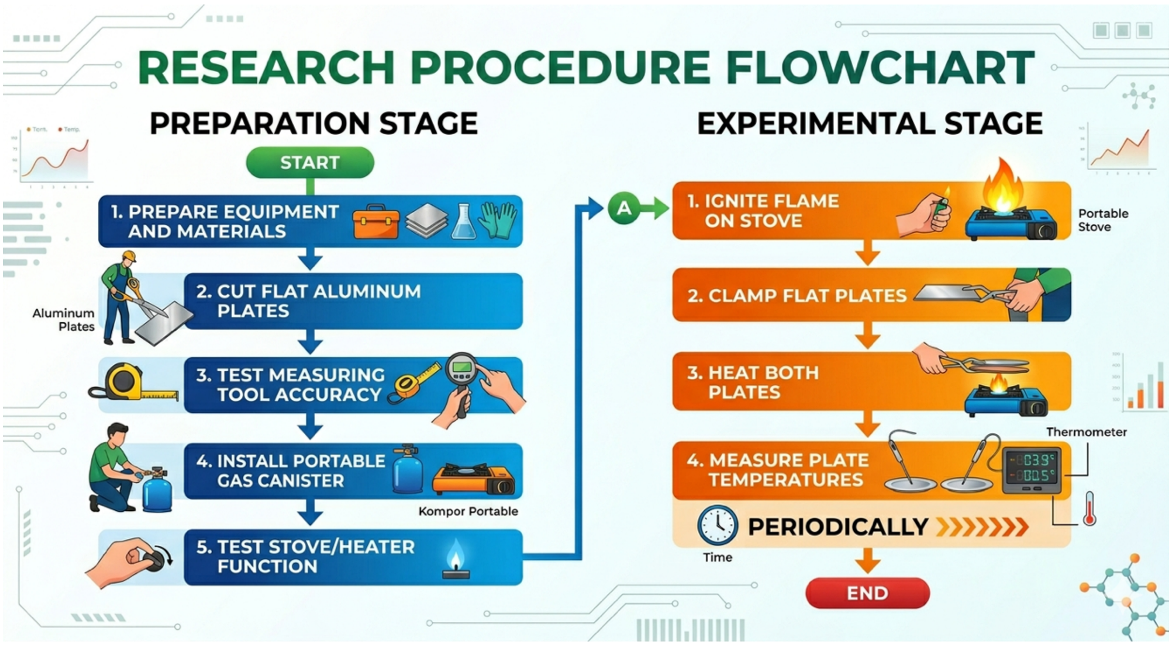

Figure 1 Research Flowchart

Figure 1 illustrates the systematic research workflow divided into two main stages: the preparation stage and the experimental stage. The preparation stage began with the assembly of all required equipment and materials, including an aluminum plate, a portable stove, and measurement instruments. Subsequently, the aluminum plate was cut to predetermined dimensions to ensure the uniformity of the test specimens. This was followed by the verification of the measuring instruments' accuracy through a calibration process, ensuring the data validity and reliability. The next steps involved properly installing the gas cylinder on the portable stove and functional testing the stove to confirm that the heating device operates safely and provides a stable flame before use in the experiment.

The experimental stage constituted the core of the study and began with igniting the portable stove as the heat source. The aluminum plate was then securely held in tongs to ensure safe handling during heating. The plate was heated until a relatively uniform temperature was achieved across its entire surface. After heating, the plate's temperature was measured periodically with a thermometer to observe temperature variations over time. This procedure was repeated at regular intervals until sufficient data were collected, after which the experiment was concluded. Overall, the workflow depicted in the diagram demonstrated that the study was conducted in a structured, controlled manner, ensuring the reliability and validity of the results.

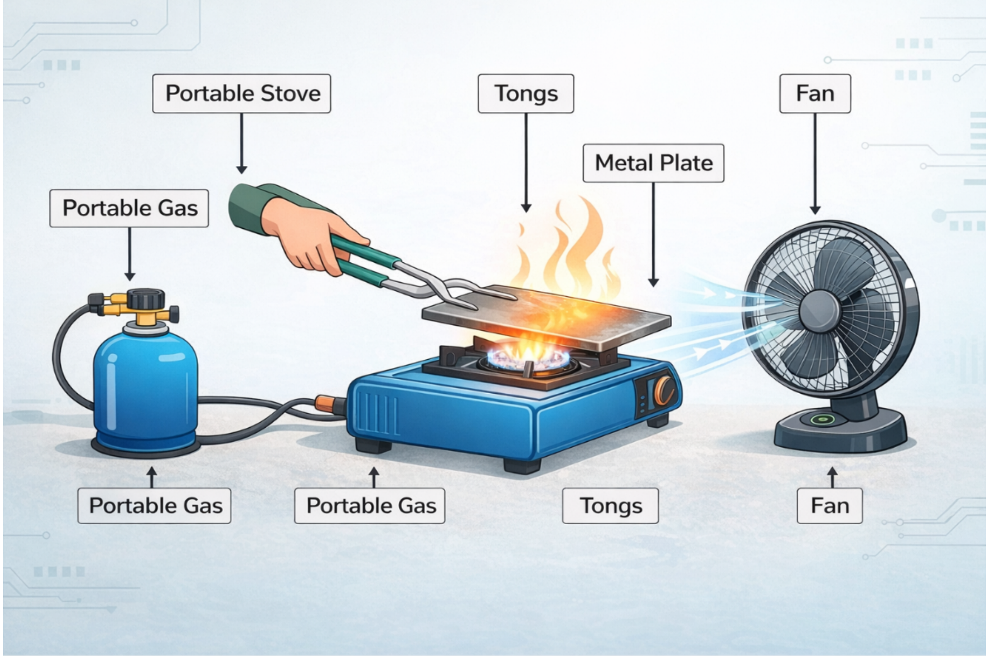

Figure 2 Experimental Setup

Figure 2 illustrates the experimental apparatus arrangement used to investigate convective heat transfer on a metal plate. The main components shown include a portable stove as the heat source, a portable gas cylinder as the fuel supply, a metal plate as the test specimen, and tongs to hold and position the plate during heating. The metal plate was heated above the stove until it reached a specified temperature, thereby creating a temperature difference between the plate surface and the surrounding air, which acted as the driving force for heat transfer.

In addition, the figure depicted the use of a fan to generate forced airflow around the metal plate. This airflow accelerated heat dissipation from the plate surface via forced convection. The combination of controlled heating and cooling via airflow enabled the observation of differences in heat transfer characteristics between natural and forced convection, particularly in the plate temperature decay rate over time.

3. Results and Discussion

The surface temperature of the metal plate was measured under two heat transfer conditions: natural convection and forced convection. In both cases, temperature measurements were obtained using an infrared thermometer at 1-minute intervals over a total duration of 5 minutes. This measurement approach enabled evaluation of transient cooling behavior over time.

Under natural convection conditions, the metal plate cooled without externally induced airflow. In contrast, during the forced convection test, airflow was generated using a fan directed toward the metal plate surface thereby increasing fluid velocity and enhancing convective heat transfer. This variation in operating conditions allowed for a direct comparison of the influence of convection mechanisms on the plate temperature decay rate.

Table 1. Temperature Data of the Metal Plate as a Function of Time under Natural and Forced Convection

No	Time (Minutes)	Natural Convection (^{0}C)	Force Convection (^{0}C)
1	0	48	47
2	1	35.3	34.6
3	2	34.6	31.4
4	3	32.9	30.9
5	4	30.8	29.1
6	5	30.8	28.5

Based on the obtained data, the plate surface temperature decreased more rapidly under forced convection than under natural convection over the same time interval. This finding clearly demonstrates that forced convection provides a higher heat transfer rate compared to natural convection.

The convective heat transfer coefficient (h) was determined to quantitatively evaluate the heat transfer performance under both conditions. The calculation was based on the measured surface temperature over time, with the ambient temperature (T∞) assumed constant at 28°C (301 K). The flat plate had dimensions of 5 cm × 2 cm, resulting in a heat transfer surface area of:

$$A = 0.05 \times 0.02 = 0.001\ m^2$$

Using experimental data and reference ranges for convection coefficients, the value of h for natural convection was estimated to be 20 W/m²·K, while for forced convection it was approximately 50 W/m²·K. The higher value under forced convection reflected the increased heat transfer capability resulting from enhanced fluid motion and surface mixing. These coefficient values were subsequently used to calculate the convective heat transfer rate in the following subsection.

The convective heat transfer rate (q) was subsequently calculated using the measured h and the temperature difference between the plate surface (Ts) and the ambient environment (T∞). A summary of the calculated convective heat transfer rates for those mechanisms was presented as follows.

Table 2. Results of Natural Convective Heat Transfer Rate (q) Calculation

Coef. Convection (W/m^{2}K)	Time (Minutes)	$T\infty$(K)	Ts (K)	Cross-Sectional Area (m^2)	Convection Rate q (W)
20	0	301	321	0.001	0.40
20	1	301	308.30	0.001	0.15
20	2	301	307.60	0.001	0.13
20	3	301	305.90	0.001	0.10
20	4	301	303.80	0.001	0.06
20	5	301	303.8	0.001	0.06

Table 3. Results of Forced Convective Heat Transfer Rate (q) Calculation

Coef. Convection (W/m^{2}K)	Time (Minutes)	$T\infty$(K)	Ts (K)	Cross-Sectional Area (m^2)	Convection Rate q (W)
50	0	301	320	0.001	0.95
50	1	301	308	0.001	0.33
50	2	301	304	0.001	0.17
50	3	301	304	0.001	0.15
50	4	301	302	0.001	0.06
50	5	301	302	0.001	0.03

The two tables above were then compared in the following graph:

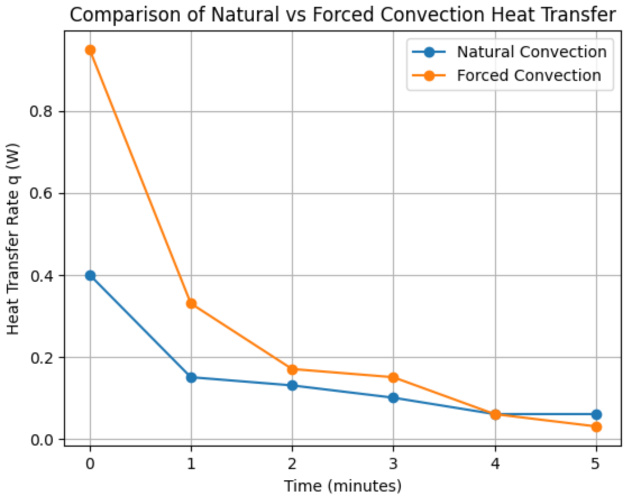

Figure 3 Graphic Comparison of Natural Convection and Force Convection Heat Transfer

Based on the experimental results presented in Table 3, a comprehensive analysis was conducted to evaluate the heat transfer characteristics of the flat plate under natural convection and forced convection conditions. This analysis included the temperature decay rate and the heat transfer effectiveness.

The results indicated that the heat transfer rate was highest at the initial stage of cooling (t = 0 min) for both conditions, reaching 0.95 W under forced convection and 0.40 W under natural convection. As time progressed, the value of q decreased for both mechanisms. This trend was consistent with Newton's law of cooling, which stated that the heat transfer rate was proportional to the temperature difference ($T_s - T_\infty$). As the plate temperature approached the ambient temperature, the temperature gradient decreased, leading to a reduction in heat transfer rate [7].

The temperature profiles further demonstrated that cooling under natural convection occurred more gradually, with the plate temperature decreasing from 321 K to 303.8 K over 5 minutes. This behavior was attributed to limited fluid motion driven solely by buoyancy forces. In contrast, under forced convection, the temperature decreased more significantly, reaching approximately 301.65 K within the same duration. The enhanced cooling performance was associated with increased airflow velocity, which reduced the thermal boundary layer thickness and promoted more efficient heat transfer.

The observed differences in heat transfer behavior highlighted the critical role of fluid flow velocity in convection mechanisms. In forced convection, the externally induced airflow increases turbulence intensity and enhanced energy transport from the solid surface to the surrounding fluid. As a result, the convective heat transfer coefficient became significantly higher than that of natural convection, where fluid motion was relatively weak and driven only by density gradients [8].

In the context of thermal engineering, these findings have important implications for the application of natural cooling in industrial machinery to support green industry initiatives and energy conservation. Natural convection, as part of a natural cooling mechanism, can be utilized as a passive cooling method without requiring additional energy input, thereby operational energy consumption in industrial cooling systems can be reduced. Although the heat transfer rate in natural convection was lower than that in forced convection, optimization strategies, such as increasing surface area, using materials with high thermal conductivity, and improving ventilation, can enhance the effectiveness of natural cooling [11].

Therefore, the integration of natural cooling systems in industrial machinery has the potential to reduce dependence on active cooling systems that rely on electrical energy. This aligns with the principles of green industry, which emphasize energy efficiency, emission reduction, and the utilization of natural mechanisms in industrial processes. Consequently, a thorough understanding of convective heat transfer characteristics, both natural and forced, is essential for designing more sustainable and environmentally friendly cooling systems.

4. Conclusion

The results indicate that forced convection produced a higher heat transfer coefficient (50 $W/m^2 \cdot K$) than natural convection (20 $W/m^2 \cdot K$), resulting in a faster temperature reduction. The maximum heat transfer rate occurred at the initial stage, reaching 0.95 W for forced convection and 0.40 W for natural convection, and decreased over time as the temperature difference between the plate surface and the ambient environment diminished.

These findings demonstrate that airflow significantly enhances heat transfer performance by increasing the heat transfer coefficient by up to twofold. However, natural convection remains an effective passive cooling method due to its energy efficiency, as it requires no additional energy input. With appropriate design optimization, natural convection systems can be equivalent to forced convection and contribute to sustainable and energy-efficient thermal management solutions.

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