



## ANALYSIS OF THE EFFECT OF SURFACE EMISSIVITY AND TEMPERATURE ON RADIATION HEAT TRANSFER RATE IN METAL MATERIALS

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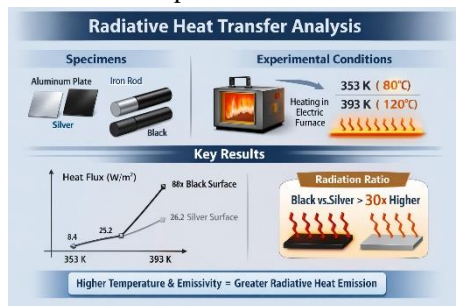
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### Graphical Abstract



### Abstract

This study examines the characteristics of radiative heat transfer in metal specimens with different surface coatings. The experiment utilized two materials: an aluminum plate and an iron rod, each coated with either black or silver paint. Specimens were heated in an electric furnace at 80°C and 120°C (353 K and 393 K), and the resulting radiative heat flux from each surface was analyzed. Heat flux was calculated using the heat flux equation, and the influence of surface coating was assessed by comparing the radiation ratio between black and silver surfaces. The results indicate that radiative heat flux increases substantially with temperature for all specimens. Black-coated surfaces exhibited significantly higher heat flux values than silver-coated surfaces, attributable to their greater emissivity. At 393 K, the heat flux for the black-coated aluminum plate reached 848.89 W/m<sup>2</sup>, whereas the silver-coated aluminum plate produced only 25.17 W/m<sup>2</sup>. A comparable pattern was observed for the iron rod specimens. Radiation-ratio analysis shows that the heat flux from black surfaces can exceed that from silver surfaces by more than 30 times under identical conditions. These findings confirm that surface emissivity and temperature are critical factors influencing radiative heat transfer. The experimental results align with the fundamental theory of thermal radiation, showing that increased temperature and emissivity enhance radiative heat transfer.

Keywords: Radiative heat transfer, heat flux, emissivity, surface coating, Stefan–Boltzmann law, thermal radiation.

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## 1. Introduction

Heat transfer is a fundamental concept in physics and engineering that describes the transfer of thermal energy between objects due to temperature differences [1]. This process occurs whenever a spatial temperature gradient exists within a medium or between two distinct media. A thorough understanding of heat transfer mechanisms is essential for a wide range of engineering applications, including thermal system design, energy conversion systems, industrial heating, and electronic cooling.

Heat transfer generally occurs through three primary mechanisms: conduction, convection, and radiation. Conduction involves the transfer of heat through a solid material without macroscopic movement of matter. Convection refers to heat transfer between a surface and a moving fluid, or within the fluid itself, as a result of fluid motion. Radiation is the transfer of thermal energy via electromagnetic waves and does not require

a medium [2]. Radiative heat transfer becomes particularly significant at elevated temperatures or when heat exchange occurs between surfaces separated by air or vacuum [3]. Radiative heat transfer is strongly influenced by the surface characteristics of materials, particularly their emissivity. Emissivity represents the ability of a surface to emit thermal radiation relative to that of an ideal black body, with values ranging from 0 to 1. Surfaces with higher emissivity are more effective in emitting and absorbing thermal radiation. Surface properties, such as color, roughness, and coating conditions, can significantly affect emissivity [4]. Dark surfaces, especially black coatings, generally exhibit high emissivity and tend to absorb and emit radiation more effectively. In contrast, reflective metallic surfaces such as polished aluminum or silver coatings have lower emissivity and tend to reflect most incident radiation.

Experimental studies have demonstrated that surface coatings and colors significantly influence thermal radiation performance. For instance, research on coated aluminum surfaces indicates that black coatings increase emissivity and enhance thermal radiation capability compared to reflective metallic surfaces [5]. Similarly, measurements of thermal radiation from surfaces of different colors show that black surfaces emit greater thermal radiation due to higher emissivity [6]. Furthermore, studies on radiant heat transfer systems reveal that increasing surface emissivity can substantially improve the effectiveness of thermal radiation exchange between surfaces [7]. Variations in surface emissivity led to differences in the rate of radiative heat transfer. Surfaces with high emissivity emit more thermal energy at the same temperature than those with lower emissivity. Reflective metal surfaces generally exhibit very low emissivity, while coated or oxidized surfaces can exhibit much higher emissivity [8], [9], [10]. Recognizing these differences is crucial for optimizing heat transfer performance in engineering applications, including solar collectors, thermal insulation systems, and heat exchanger design [11], [12], [13]. This study aims to experimentally investigate the effects of surface temperature and surface color, specifically black and silver coatings, on the rate of radiative heat transfer from aluminum plates and iron rods. Additionally, the research evaluates whether material type or surface emissivity, as influenced by surface color, has a greater impact on the magnitude of thermal radiation emitted. The findings are expected to enhance understanding of radiative heat transfer behavior and inform its application in thermal engineering systems.

## **2. Method**

### **2.1. Research Design**

A quantitative experimental approach was utilized to examine the characteristics of radiative heat transfer from metal surfaces under different temperature and surface conditions. This method allows direct measurement and observation of heat radiation emitted by solid materials in controlled laboratory environments. The effects of surface temperature, material type, and surface coating on thermal radiation rate were quantitatively analyzed using this approach. The experiment was conducted at the Thermal Engineering Laboratory, 2<sup>nd</sup> Floor, Building A7, Dept of Mechanical Engineering, Universitas Negeri Surabaya (UNESA). The laboratory environment maintained controlled conditions to minimize the influence of external disturbances, including airflow, fluctuating environmental temperatures, and other uncontrolled heat transfer mechanisms [14]. The experimental setup was specifically designed to measure the thermal radiation emitted by metal specimens after heating to predetermined temperature levels.

The specimens consisted of plate and cylinder samples with different surface coatings. Black and silver paints were applied to produce variations in surface emissivity. Surface emissivity is a critical parameter in radiative heat transfer because it determines the efficiency with which a surface emits thermal radiation. By varying both the material type and surface coating, the experiment aimed to determine how these factors affect the magnitude of radiative heat transfer from the specimen surfaces.

### **2.2. Experimental Materials and Equipment**

The experiment utilized several materials and instruments to generate, measure, and record thermal radiation from metal surfaces. The primary specimens used in the study were aluminium plates and iron cylinders with uniform dimensions to ensure consistent surface areas and comparable heat-transfer conditions. Each specimen was coated with either black paint or silver paint to produce different emissivity characteristics. The coating process was performed carefully to ensure uniform thickness and surface coverage. An electric furnace served as the primary heat source, raising the specimens' temperature to predetermined levels between 80°C and 120°C. This approach provided stable heating and ensured uniform temperature distribution across the specimen surfaces. Temperature measurements were obtained using

thermocouples connected to a data logger. Thermocouples were attached directly to the specimen surfaces to ensure accurate surface temperature readings during heating. The ambient laboratory temperature was also monitored to determine the temperature gradient between the specimen surface and the surrounding environment. Additional equipment included a specimen holder placed inside the furnace, an insulated base to minimize conductive heat loss, and precision measurement tools for determining specimen dimensions such as length, diameter, and surface area. These measurements were essential for calculating the radiative heat transfer rate using the Stefan–Boltzmann equation.

### 2.3. Research Variables

The study incorporated independent, dependent, and control variables. The independent variables, which were systematically varied, included the specimen surface temperature and the type of material with different surface coatings. Surface temperature was adjusted to five levels: 80°C, 90°C, 100°C, 110°C, and 120°C. Four specimen conditions were examined: aluminum with a black coating, aluminum with a silver coating, iron with a black coating, and iron with a silver coating. The dependent variable was the rate of radiative heat transfer from each specimen surface, representing the thermal energy emitted by the heated metal into the environment. This value was calculated from measured temperatures and the surface emissivities of the materials. Control variables included the dimensions and surface area of the specimens, which were kept identical for all specimens. The ambient laboratory temperature was maintained at approximately 27°C during testing, and environmental conditions were kept stable to minimize external disturbances that could affect heat transfer. The emissivity values used in the calculations were obtained from reliable literature sources. The system was maintained under steady-state conditions before each measurement was recorded to ensure stable temperature conditions during data collection.

### 2.4. Experimental Procedure

The experimental procedure comprised several stages to ensure consistent and reliable data collection. Initially, specimens were prepared by coating the metal surfaces with either black or silver paint to create differences in emissivity. The coating was applied uniformly to prevent irregularities that might affect radiation. Following preparation, each specimen was placed in the electric furnace and gradually heated to the target temperature. Surface temperature was continuously monitored using thermocouples connected to the data logger. Upon reaching the desired temperature, the system was allowed to stabilize until steady-state conditions were achieved, ensuring constant specimen temperature and equilibrium in heat transfer processes. Once steady-state conditions were established, both the specimen surface temperature and the ambient temperature were recorded using the data logging system. Measurements were performed at each temperature level for every specimen variation. This procedure was repeated for all specimen types to obtain a comprehensive dataset for comparative analysis.

### 2.5. Data Analysis

The radiative heat transfer rate from the specimen surface was calculated using the Stefan–Boltzmann law [15], which relates thermal radiation to temperature and surface emissivity.

$$q = \epsilon\sigma A (T_s^4 - T_{env}^4) \quad (1)$$

where  $q$  is the radiative heat transfer rate (W),  $\epsilon$  is the surface emissivity,  $\sigma$  is the Stefan–Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ),  $A$  is the surface area ( $\text{m}^2$ ),  $T_s$  is the surface temperature (K), and  $T_{env}$  is the ambient temperature (K). The experimental temperature data were used to calculate the radiative heat transfer rate for each specimen condition. The calculated values were compared to evaluate the effects of temperature variation, material type, and surface coating on radiative heat transfer. A graphical analysis was conducted to examine the relationship between surface temperature and the rate of heat radiation. This analysis identified the dominant factors affecting radiative heat transfer, particularly whether material type or surface emissivity due to coating color exerted a greater influence on the magnitude of thermal radiation.

$$q'' = \frac{q}{A} \quad (2)$$

Equation (2) is used to determine the heat flux, which represents the rate of heat transfer per unit surface area. Heat flux indicates how much thermal energy is emitted from a surface relative to its area. This equation shows that the heat flux is obtained by dividing the total heat transferred by a surface by its area. Using heat flux allows researchers to compare the thermal radiation performance of specimens with different sizes or geometries, as the heat transfer value is normalized by the surface area.

$$R = \frac{q_{black}}{q_{silver}} \quad (3)$$

Equation (3) is used to determine the radiation ratio, which compares radiative heat transfer between black-coated and silver-coated surfaces. This ratio is used to evaluate the effect of surface emissivity on thermal radiation. A value greater than one indicates that the black surface emits more thermal radiation than the silver surface. This occurs because black coatings generally have higher emissivity, enabling them to radiate thermal energy more efficiently. In contrast, silver surfaces have very low emissivity and tend to reflect thermal radiation, resulting in much lower heat emission. Therefore, these two equations are used to analyze the radiative heat transfer intensity and to compare the radiation performance of surfaces with different emissivities.

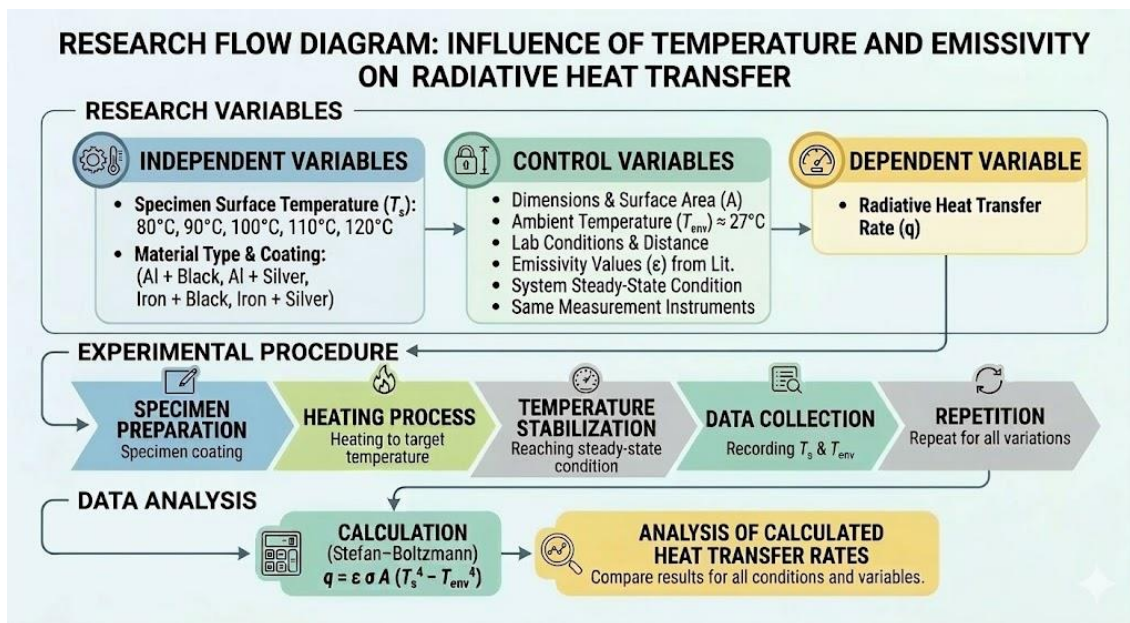
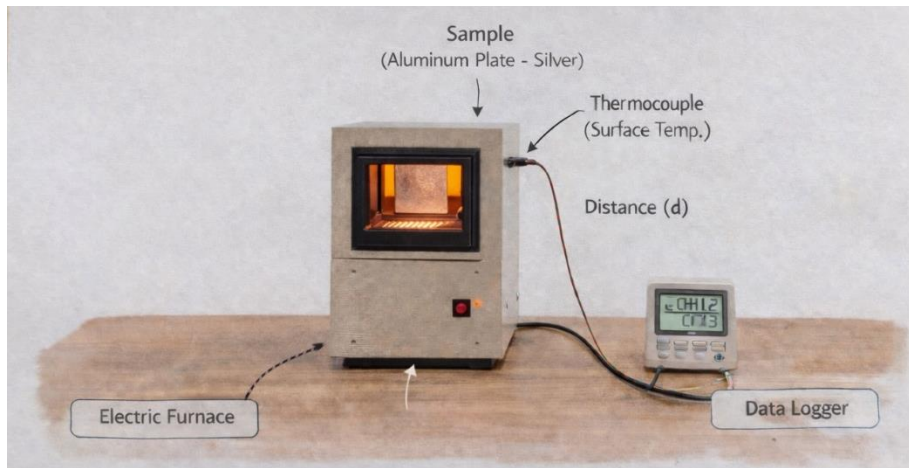


Figure 1 Research Flowchart

Figure 1 shows the flowchart of the experimental procedure used in this study. The flowchart illustrates the sequence of the research process, starting with specimen preparation, coating application, heating the specimen in an electric furnace, temperature measurement using thermocouples connected to a data logger, data recording, and, finally, data analysis using the Stefan–Boltzmann equation to determine the radiative heat transfer rate.

Figure 2 shows the experimental setup used to conduct the radiative heat transfer test. In this setup, the metal specimen is placed in an electric furnace to achieve the desired temperature. The surface temperature of the specimen is measured with thermocouples connected to a data logger, and the ambient temperature is also monitored throughout the experiment. This configuration allows the measurement of the temperature difference between the specimen surface and the surrounding environment, which is required to calculate the radiative heat transfer rate.



**Figure 2 Experimental Setup**

### 3. Results and Discussion

The experiment investigated the surface temperature characteristics of metal specimens under controlled heating conditions. Two materials were analyzed: an aluminum plate and an iron rod, each coated with black or silver paint. The primary objective was to evaluate the influence of surface emissivity and specimen geometry on radiative heat transfer. Specimens were heated to temperature levels ranging from 353 K to 393 K. Surface temperatures were recorded using an infrared thermometer after thermal equilibrium was established. Due to differences in geometry and thermal mass, the aluminum plates required approximately 15 seconds of heating, while the iron rods required 1 minute to reach a stable temperature.

Table 1. Specimen surface temperature

Specimen	Heating Temperature (K)	Surface Temperature $T_s$ (°C)	Heating Time
Aluminum Plate (Silver)	353	65	15 s
	363	79	15 s
	373	86	15 s
	383	106	15 s
	393	116	15 s
Aluminum Plate (Black)	353	75	15 s
	363	85	15 s
	373	95	15 s
	383	109	15 s
	393	118	15 s
Iron Rod (Silver)	353	60	1 min
	363	71	1 min
	373	92	1 min
	383	98	1 min
	393	114	1 min
Iron Rod (Black)	353	70	1 min
	363	86	1 min
	373	95	1 min
	383	107	1 min
	393	118	1 min

Based on Table 1, the results demonstrate that black-coated specimens consistently exhibit higher surface temperatures than silver-coated specimens under identical heating conditions. This outcome is attributed to the greater absorption of thermal radiation by darker surfaces, whereas reflective surfaces, such as silver, reflect a significant portion of the incident heat. Radiative heat transfer for each specimen was determined using the Stefan–Boltzmann equation, which quantifies thermal radiation as a function of temperature and emissivity. Emissivity values applied in this experiment were 0.98 for black paint and 0.03 for silver paint. The ambient temperature was maintained at 27°C (300 K). Surface areas were calculated based on specimen geometry: the iron rod area was determined using the equation for the surface area of a cylinder, yielding 0.00503 m<sup>2</sup>, and the aluminum plate area was calculated using the equation for the area of a rectangle, yielding 0.0018 m<sup>2</sup>.

Figure 3 presents the relationship between heating temperature and radiative heat transfer rate for four specimens: *plate silver*, *plate black*, *rod silver*, and *rod black*. The radiative heat transfer rate increases as the heating temperature rises from approximately 353 K to 393 K. This trend is evident for all specimens, although the extent of the increase differs among them. Such behavior aligns with the theory of thermal radiation, which states that the energy emitted by a surface increase with its absolute temperature. According to the Stefan–Boltzmann law, the radiative heat transfer rate is proportional to the fourth power of the surface temperature. Therefore, even a small increase in temperature can lead to a substantial increase in emitted radiation. A pronounced difference exists between specimens coated with black paint and those coated with silver paint. At identical temperatures, black-coated specimens exhibit significantly higher radiative heat transfer rates than silver-coated specimens. This difference arises because black surfaces have higher emissivity, enabling more efficient thermal radiation. Conversely, silver surfaces have very low emissivity and predominantly reflect thermal radiation rather than emit it. For instance, at a heating temperature of approximately 393 K, the radiative heat transfer rate of the black rod is about 4.27 W, while the silver rod produces only 0.12 W. This demonstrates the substantial impact of surface emissivity.

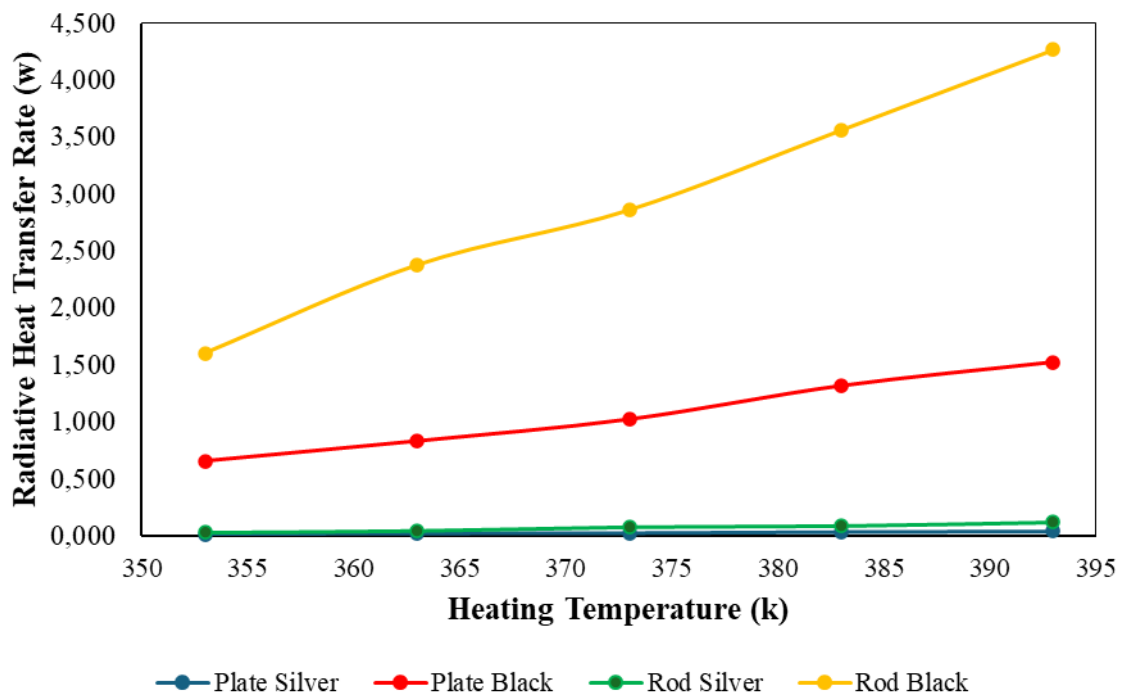


Figure 3. Radiative heat transfer rate

Beyond emissivity, the geometry and surface area of the specimens also affect the magnitude of radiative heat transfer. The graph indicates that rod specimens generally achieve higher radiation rates than plate specimens, especially for black-coated surfaces. This is attributed to the rod's larger effective surface area, which facilitates greater thermal energy emission. According to the data, the order of radiative heat transfer performance from highest to lowest is rod black, plate black, rod silver, and plate silver. These trends align with the fundamental principles of radiative heat transfer, which state that the radiation rate increases with temperature, emissivity, and surface area.

Table 2. Heat Flux calculation

Specimen	Temperature (K)	Heat Flux (W/m <sup>2</sup> )
Aluminum Plate Silver	353	8.42
	393	25.17
Aluminum Plate Black	353	364.83
	393	848.89
Iron Rod Silver	353	7.16
	393	24.45
Iron Rod Black	353	319.08
	393	848.31

Table 3 presents the variation in radiative heat flux for different specimens at two heating temperatures: 353 K and 393 K. Heat flux increases substantially with rising temperature, as thermal radiation is highly dependent on the absolute temperature of the emitting surface. The Stefan–Boltzmann law states that the radiative heat transfer rate increases rapidly with temperature, leading to higher heat flux at elevated temperatures. A distinct difference exists between black-coated and silver-coated surfaces. Specimens coated with black paint exhibit significantly higher heat flux than those coated with silver paint. For example, the heat flux of the black-coated aluminum plate increases from approximately 364.83 W/m<sup>2</sup> at 353 K to 848.89 W/m<sup>2</sup> at 393 K, whereas the silver-coated aluminum plate increases only from 8.42 W/m<sup>2</sup> to 25.17 W/m<sup>2</sup> over the same temperature range. This substantial difference is attributed to the high emissivity of black surfaces, which enables efficient emission of thermal radiation. Conversely, silver surfaces possess very low emissivity and predominantly reflect thermal radiation.

Specimen geometry also influences heat flux behavior. The black-coated iron rod generates a heat flux of approximately 319.08 W/m<sup>2</sup> at 353 K, increasing to 848.31 W/m<sup>2</sup> at 393 K, which is consistent with the trend observed for the black-coated aluminum plate. These results indicate that while geometry affects total radiative heat transfer, surface emissivity remains the primary factor governing radiation intensity. In summary, the results demonstrate that heat flux increases with both temperature and emissivity, consistent with fundamental radiative heat transfer theory. The substantially higher heat flux values for black-coated specimens confirm that surfaces with higher emissivity emit thermal radiation more effectively than reflective surfaces such as silver coatings.

Table 3. Radiation ratio

Specimen	Temperature (K)	q" Black (W/m <sup>2</sup> )	q" Silver (W/m <sup>2</sup> )	Radiation Ratio
Aluminum Plate	353	364.83	8.42	43.33
Aluminum Plate	393	848.89	25.17	33.73
Iron Rod	353	319.08	7.16	44.56
Iron Rod	393	848.31	24.45	34.70

The table 3 show that the radiative heat flux from black surfaces is approximately 33–45 times that from silver surfaces at the same temperature. This large difference arises because black coatings have a much higher emissivity, enabling them to radiate thermal energy more efficiently. In contrast, silver coatings have very low emissivity and tend to reflect most of the thermal radiation. This result confirms that surface emissions play a dominant role in determining radiative heat transfer performance.

#### 4. Conclusion

The experimental results and analysis indicate that the radiative heat transfer characteristics of the specimens are strongly influenced by temperature, surface emissivity, and material geometry. When the heating temperature increases from 353 K to 393 K, the radiative heat flux of all specimens increases significantly. This observation aligns with the theory of thermal radiation, which states that the radiative heat

transfer rate increases rapidly with increasing surface temperature. The results demonstrate a clear distinction between black-coated and silver-coated surfaces. Black-coated specimens exhibit substantially higher heat flux values than silver-coated specimens at the same temperature. For instance, the heat flux of the black-coated aluminum plate increases from 364.83 W/m<sup>2</sup> to 848.89 W/m<sup>2</sup>, whereas the silver-coated aluminum plate increases only from 8.42 W/m<sup>2</sup> to 25.17 W/m<sup>2</sup>. A similar trend is observed for the iron rod specimens. This difference arises because black surfaces have higher emissivity, enabling more effective emission of thermal radiation, while silver surfaces primarily reflect it. Additionally, analysis of the radiation ratio indicates that the radiative heat flux from black surfaces can be approximately 30-45 times greater than that from silver surfaces under identical conditions. This finding confirms that surface emissivity is a dominant factor in determining radiative heat transfer performance. Overall, the experimental results align with the fundamental principles of radiative heat transfer and demonstrate that higher temperature and higher emissivity result in greater thermal radiation emissions.

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