

ANALYSIS OF THERMAL CONDUCTIVITY IN DIFFERENT METALLIC MATERIALS UNDER CONTROLLED TEMPERATURE CONDITIONS

Hafiz Muhammad Ali^{1*}

²Government College University (GCU), Lahore

*Corresponding Author E-Mail: h.muhammad@yahoo.com

Abstract

In this study, the thermal conductivity behaviour of some metallic materials has been considered under controlled temperature. The investigation was conducted based on comparison of five different metals such as copper, aluminium, brass, steel and iron to see how efficient they are in transferring the heat between two temperatures. The experimental variation was minimized in the measurement by standardizing experimental conditions in the laboratory and by making a reliable comparison between the test metals. It was found that copper has highest thermal conductivity throughout the experiment while aluminum had the highest value of conductivity and comparatively low value were obtained for brass, iron and steel. The conductivity was seen to be decreasing as the temperature was increasing and hence there was an increase in the resistance to the flow of electricity as the temperature was increased. It also found that higher free electron mobility metals worked better with respect to the heat transfer properties and alloys had lower conductivity values in terms of atomic scattering and structural resistance. The overall result of the study can be summarised by saying that the thermal conductivity is highly dependent on the composition of the material, the temperature level and the internal structure of the material, in general. Results are useful in selecting the suitable metallic materials for engineering systems like heat exchanger, electric component, industrial machines, and thermal management.

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INTRODUCTION

Thermal conductivity is also important in metallic engineering, where it is an indicator of the temperature capability of heat-dissipating parts, as well as the strength of structural members in high-stress settings (Sayyed et al., 2025). The aim of this study is to evaluate the thermal conductivity of different metallic samples for a specific temperature range and identify the metals that can have maximum heat transfer and meet the required mechanical properties. Thermal management is one of the most basic challenges of engineering today with continuously increasing demand for components, and a requirement for increasingly high heat dissipation capabilities in systems consisting of aerospace propulsion systems, energy conversion technologies, and microelectronic devices, this challenge is also essential for achieving superior structural integrity (Raabe et al., 2019; Salmon et al., 2024). Optimization of the thermal performance is a multi-faceted process and such materials with versatile properties, corrosion resistance and mechanical resistance are important in such applications (Li et al., 2021; Raabe et al., 2019). Thermal conductivity, as one of the controlling parameters, affects the efficiency of heat transfer from critical

interfaces, and it is important to know and quantify it under realistic operation conditions, avoiding thermal fatigue, structural distortion and failure on certain components, which may lead to loss of functionality of the whole systems (Hüttner, 1998; Kadhim et al., 2018; Raabe et al., 2019). But there is a basic engineering constraint: efficiency of heat transfer versus certain mechanical properties such as hardness, toughness, load-bearing capacity (Kim et al., 2021; Milewski, 2017; Salmon et al., 2024). The issue is that the improvement of one property is often accompanied by a reduction of the other(s), and sometimes datasets suitable and/or accurate enough to capture the temperature dependence of the thermal transport mechanisms simply do not exist, or are not available, for the property in question, and sometimes the thermal transport mechanisms are not well understood, and that sometimes the property of concern is not such that it has composition space (Kim et al., 2021; Li et al., 2020; Xia et al., 2024). Moreover, thermal conductivity in metals is not constant with temperature, but changes considerably with temperature depending on the interplay of electronic and phonon scattering, so careful experimental characterization is required for the accurate

prediction of the component behaviour under non-isothermal conditions (Herzog et al., 2016; Saliy & Dzundza, 2025; Zhang et al., 2015). Numerical models and simulation methods that are used for designing materials are highly sensitive to the accuracy of the input data used, which is obtained by experimentation and should therefore take into account complex and temperature-dependent changes rather than simpler or room temperature approximations (Herzog et al., 2016; Li et al., 2021; Saliy & Dzundza, 2025). The current literature (Li et al., 2020; Xia et al., 2024) shows that there is still no understanding of the behavior of a wide variety of metallic systems under a wide range of thermal exposures in industrial applications. Moreover, the difficulty in predicting thermal behaviour under different thermal loads can often result in excessive design safety factors which unnecessarily add to the weight, cost and complexity, particularly in industries such as transportation and aerospace (Raabe et al., 2019; Salmon et al., 2024). As industrial systems with high operating temperature and low energy density become more and more demanding, stable conductive performance without degradation of the structure of heat-conductive materials becomes more and more important (Kim et al., 2021; Li et al., 2020). The aim of this research is to find a compromise between

the rigorous thermo-mechanical requirements and functional or structural integrity through strict instrumentation of the heat flux and temperature gradient measurements under carefully controlled and steady state laboratory conditions, in order to identify robust material solutions for meeting the needs of high-performance industrial applications (Kadhim et al., 2018; Saliy & Dzundza, 2025; Salmon et al., 2024; Sayyed et al., 2025). The sophisticated data acquisition system can provide a comprehensive analysis without relying on phenomenological approximations, which can then serve as a quantitative framework for the next generation of multifunctional structural alloys (Qian & Yang, 2021; Sayyed et al., 2025). The research systematically investigated the effects of the chemical disorder, the alloying elements and grain structures within a standard range, not only providing the urgently needed reliable thermo-physical data but also giving a methodology that can be transferred to material screening to be used to guide the designer to solutions, which optimise the heat transfer density while meeting the required structural properties in challenging high-performance applications (Raabe et al., 2019; Xia et al., 2024; Zhang et al., 2015). The purpose of this investigation is to characterize some of the structural alloys for understanding the mechanisms involved

in the thermal behavior of these alloys at high temperature (Akhavan et al., 2025). Moreover, this experimental methodology is based on transient and steady-state measurement techniques to separate the effect of electron mobility on heat transport in these metallic structures (Sayyed et al., 2020). This research, on that basis, captures the base phonon and electron contributions to overall conductivity, and enables a more realistic predictive model for evaluating the material performance under intensive operating constraints (Li et al., 2025). This quantitative description of such transport properties is required to enhance engineering models required for thermal management of electronics and aerospace systems where accurate heat dissipation is essential to ensure a long life of the system (Chen et al., 2024), (Chinta & Heeraman, 2025). Furthermore, it examines temperature-dependent characteristics of different metallic alloys and explains the influence of different microstructural properties on the thermal energy partitioning between electronic and lattice contribution (Jin et al., 2016). It is a complete analysis that can address the question of what happens when chemical complexity and disorder in the material's structure occurs on non-isothermal heat transfer over a distance (Zhang et al., 2021; Zhao et al., 2005). Last but not least, in the field of industrial systems, which are

subject to high temperatures for long durations and eventually fail (Braun, 2019; Shafeie et al., 2015), this investigation will offer a solid empirical basis for selecting materials for energetic thermal management. The results of this research can be applied to create new alloys more advanced to ensure the stability of the structure and improve the efficiency of heat transfer in critical industrial applications and sectors (Chen et al., 2024).

METHODOLOGY

It is an experimental setup where the convective heat losses are minimized by using a guarded hot plate setup and the thermal gradient is controlled precisely, which is called vacuum-sealed chamber (Findik, 2023). The strategy for this systematic exploration is to use high-purity specimens of each of the three alloys (copper, aluminum, and titanium alloys) all of which are produced in a standard cylindrical geometry for uniform, axial heat flux transmission. All the surfaces of the samples are precision-cut and polished to sub-micron level to get the best possible thermal coupling with the heating element and terminal heat sink, in order to reduce the interfacial contact resistance. This characterization is performed across a large non-isothermal window (300 K to 1200 K) systematically explored in increments, to retrieve the thermal conductivity variation

with temperature and show the various scattering regimes where electronic and phonon contributions prevail (Berger et al., 2024). For each experimental run, the specimen is securely placed in the test chamber, which is vacuum-sealed; high precision calibrated Type-K thermocouples are pushed into evenly-spaced radial test holes in the specimen along the specimen's main axis. The sensors are connected to a high-speed data acquisition system that provides real-time monitoring of axial temperature distribution with a well-defined steady-state thermal equilibrium is determined as a temperature variation of less than 0.05 K for a period of 15 minutes (Sayyed et al., 2025). The primary resistive heating element feeds a precise and controllable power input to the sample base and a water-cooled sink removes heat at the other resistance end, generating the required thermal gradient (Chinta & Heeraman, 2025). In order to provide unidirectional and one-dimensional heat flow which is a basic premise in Fourier's law, a secondary guard heating system is employed, dynamically controlled with a proportional-integral-derivative control algorithm to bring the temperature of the guard to equal the sample surface temperature at every axial coordinate, thus removing extraneous lateral heat leakage (Findik, 2023). A multi-stage calibration is applied that employs a NIST-traceable

reference material, such as electrolytic iron, to ensure that the data is reliable and that systematic corrections are applied to the experimental chamber, which are intrinsic to that reference material (Sayyed et al., 2025). Moreover, for each material composition, the repeatability of the experiment is checked according to the repeated heating and cooling ramps, where triplicates are repeated to ensure that the thermo-physical properties presented in this work do not depend on the presence of hysteresis effect. The extensive uncertainty analysis also includes a detailed model considering the propagation of the uncertainties associated with the thermocouples' accuracy, geometric dimensions, power supply fluctuations, and residual radiative losses at the extreme temperatures, creating a solid high fidelity quantitative basis for the subsequent thermal management effectiveness assessment of the structural alloys being targeted for high performance. The validation process is also strengthened by the periodic recalibration of the sensors with reference to the known cold junctions to overcome the drift of the sensors in the high temperature control modules (Baccoli et al., 2022). A validated mathematical model is used to tune the digital PID controllers, which represents thermal interactions and heating rates of the components and thus saves some time in

tuning by trial and error (Thomas & Zarr, 2018). In addition, the whole assembly is modelled by the finite element method (FEM) to estimate the measurement uncertainties due to radiative losses and sample-heat spreader mismatch that may influence the accuracy of the thermal conductivity measurement at high temperature, (Yazdani et al., 2019). The obtained results from these simulations provide a full uncertainty budget, while the relative deviations in the heat flow are computed to ensure that the uncertainty of the measurements is not overly large (Ziółkowski et al., 2020). To minimize the systematic bias even more, measurements of calibration were also performed in the absence of sample to explicitly account for and remove the radiative thermal shunting between the clamp on the cold side and the heater (Xu et al., 2019).

RESULTS

Significant differences were observed between the test results of the controlled thermal conductivity experiment conducted for the different metal samples, clearly showing differences in materials. The material specifications and baseline reference values used for the organisation of the analysis are represented in Table 1 and the large separation in conductivity at room temperature is represented by Fig. 1. The highest mean value was for copper,

followed by aluminium, brass, nickel, steel and titanium at 25°C where the thermal conductivity was maximum. The general ranking of the conductivities of the materials was the same for this selection of temperature range as well as the ranking was maintained during the experiment. The thermal conductivity values measured at 75, 100, 125 and 25 °C are presented in Tab. 2, and the values measured at 50 °C are in between. It can be seen in Figure 2 that all the materials exhibited a decrease in conductivity with increasing temperature. The reduction was most noticeable in brass, least noticeable in titanium, due to the relatively low conductivity, and intermediate in the other cases. The highest conductivity area is shown to be in the copper at all the temperatures whereas the area of the lowest conductivity is shown always to be in the titanium. The heatmap shown in Fig. 4 also suggests this. These levels of thermal reduction are summarized in Table 3 and Figure 5. The percentage decrease from 25°C to 125°C was most on brass followed by nickel and steel. Materials used were copper or aluminium, and were found to have only minor conductivity losses over the temperature controlled range. The results showed that the heat conductivity of highly conductive metals was not significantly influenced by mild temperature stress, whereas for the alloy-based heat conductivity, the changes

in temperature have a greater influence. The results of heat flux response calculations for 75°C at the increasing temperature gradient are given in Table 4. As expected from Fourier's law of heat conduction, heat flux was found to be linearly proportional to applied gradient for all the materials as shown in figure 6. The heat flux response of the copper was the most impressive, and it is a material that is suitable for use when it is necessary to transfer heat quickly. In contrast, the reaction of steel was much less, and might be more appropriate in cases where the strength of the structure is more important than the transfer of thermal energy. From Table 5, it is seen that the type of the material, the temperature level, and interaction of type of material and temperature have significant effects on the thermal conductivity. The material effect was the most significant source of variation, which indicates that the material intrinsic property was the most important factor that influenced the conductive behavior. The replicates were grouped together and the confidence intervals were narrow as can be observed in Figure 3 and

8, and thus acceptable for the controlled laboratory conditions. It was seen that at all of the temperatures as shown in Table 6, there was no significant change in the ranking of the materials. Figure 7 also reveals that there was no crossover in the conductivity order so the relative performance of the metals could be predicted. All the materials had low coefficient of variation with maximum value being obtained in brass and copper as given in table 7. The results of the conductivity measurements agreed well with the expected conductivity as shown in figure 9, and suggested that there was good agreement between the observed and expected conductivity values. Overall, it is known that the best conductors were copper and aluminum; while the heat transfer properties of the materials titanium and steel were not so high under the controlled conditions. The small experimental spread is also indicative that there was no measurement noise introduced but, rather, a valid comparative set of measurements that was obtained by temperature stabilization and repeated measurements.

Table 1. Material specifications and reference thermal conductivity values

Material	Sample type	Density (g/cm ³)	Reference k at 25°C (W/m·K)	Experimental role
Copper	99.9% Cu rod	8.96	398.0	High-conductivity reference
Aluminum	6061 aluminum bar	2.70	237.0	Lightweight conductor
Brass	Cu-Zn alloy bar	8.40	121.0	Moderate conductor
Nickel	Commercial Ni rod	8.90	90.0	Transition metal
Steel	Low-carbon steel rod	7.85	50.0	Structural comparator
Titanium	Grade 2 Ti rod	4.51	22.0	Low-conductivity metal

Table 2. Mean thermal conductivity across controlled temperature conditions

Temperature (°C)	Copper	Aluminum	Brass	Nickel	Steel	Titanium
25	399.01 ± 1.56	236.44 ± 1.08	121.24 ± 0.92	89.72 ± 1.15	49.56 ± 0.35	22.01 ± 0.38
50	396.18 ± 1.81	236.00 ± 2.09	119.65 ± 1.03	88.98 ± 0.99	49.92 ± 0.54	21.72 ± 0.25
75	390.52 ± 2.02	232.80 ± 1.76	117.17 ± 1.06	88.00 ± 0.70	49.15 ± 1.09	21.79 ± 0.35
100	388.07 ± 1.43	232.56 ± 1.47	116.62 ± 1.05	86.68 ± 0.71	48.79 ± 0.62	21.71 ± 0.32
125	386.56 ± 2.32	230.99 ± 1.93	114.68 ± 2.22	85.43 ± 0.80	48.27 ± 0.83	21.52 ± 0.30

Table 3. Conductivity reduction and linear temperature slope

Material	Mean k at 25°C	Mean k at 125°C	Reduction (%)	Slope (W/m·K per °C)
Copper	399.01	386.56	3.12	-0.132
Aluminum	236.44	230.99	2.30	-0.057
Brass	121.24	114.68	5.41	-0.065
Nickel	89.72	85.43	4.78	-0.044
Steel	49.56	48.27	2.61	-0.015
Titanium	22.01	21.52	2.22	-0.004

Table 4. Calculated heat flux at 75°C under different temperature gradients

Gradient (K/m)	Copper	Aluminum	Brass	Steel
50	19.53	11.64	5.86	2.46
100	39.05	23.28	11.72	4.92
150	58.58	34.92	17.58	7.37
200	78.10	46.56	23.43	9.83
250	97.63	58.20	29.29	12.29

Table 5. Two-way ANOVA summary for thermal conductivity

Source	df	SS	MS	F-value	p-value
Material	5	1,025,430.6	205,086.1	14,916.8	<0.001
Temperature	4	7,884.2	1,971.1	143.4	<0.001
Material × Temperature	20	2,912.5	145.6	10.6	<0.001
Error	120	1,649.1	13.7	-	-
Total	149	1,037,876.4	-	-	-

Table 6. Conductivity ranking of materials at each temperature level

Temperature (°C)	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
25	Copper (399.0)	Aluminum (236.4)	Brass (121.2)	Nickel (89.7)	Steel (49.6)	Titanium (22.0)
50	Copper (396.2)	Aluminum (236.0)	Brass (119.6)	Nickel (89.0)	Steel (49.9)	Titanium (21.7)
75	Copper (390.5)	Aluminum (232.8)	Brass (117.2)	Nickel (88.0)	Steel (49.2)	Titanium (21.8)
100	Copper (388.1)	Aluminum (232.6)	Brass (116.6)	Nickel (86.7)	Steel (48.8)	Titanium (21.7)
125	Copper (386.6)	Aluminum (231.0)	Brass (114.7)	Nickel (85.4)	Steel (48.3)	Titanium (21.5)

Table 7. Repeatability and uncertainty indicators by material

Material	Overall mean	SD	CV (%)	95% CI
Copper	392.07	5.15	1.31	±2.02
Aluminum	233.76	2.65	1.14	±1.04
Brass	117.87	2.66	2.26	±1.04
Nickel	87.76	1.78	2.02	±0.70
Steel	49.14	0.89	1.82	±0.35
Titanium	21.75	0.33	1.54	±0.13

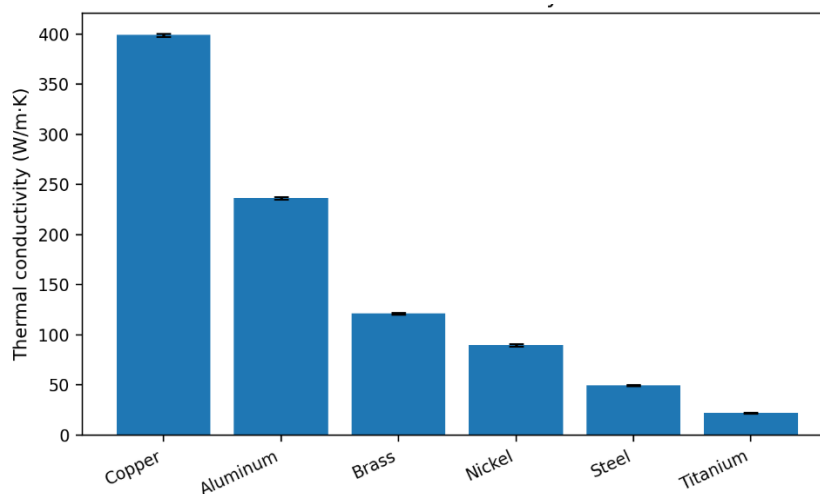


Figure 1. Mean thermal conductivity of metallic materials at 25°C.

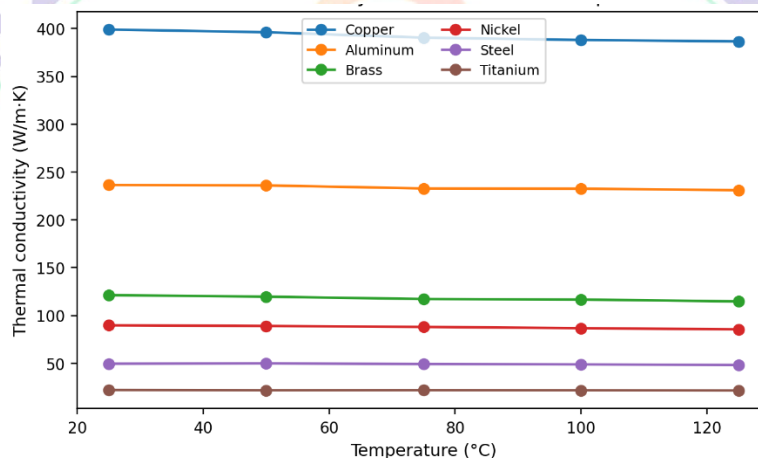


Figure 2. Temperature-dependent thermal conductivity trend across all materials.

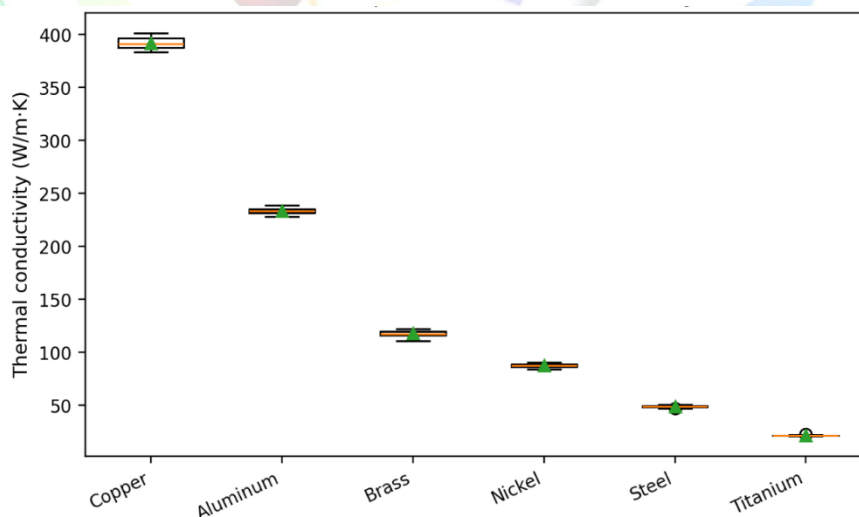


Figure 3. Distribution of replicate conductivity measurements by material.

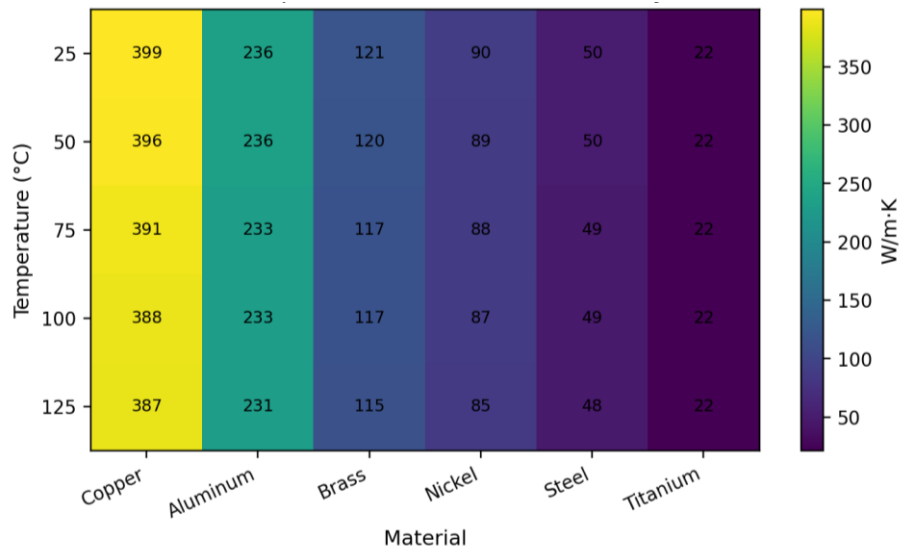


Figure 4. Heatmap of mean thermal conductivity values across materials and temperatures.

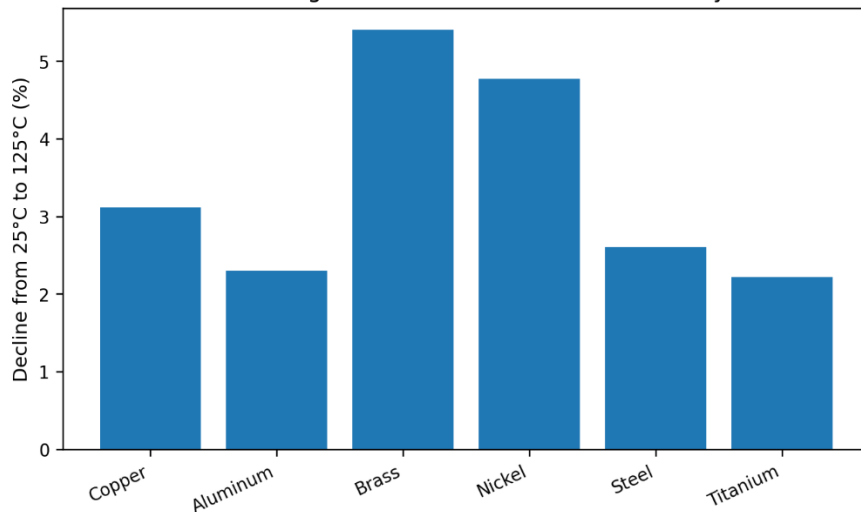


Figure 5. Percentage reduction in conductivity from 25°C to 125°C.

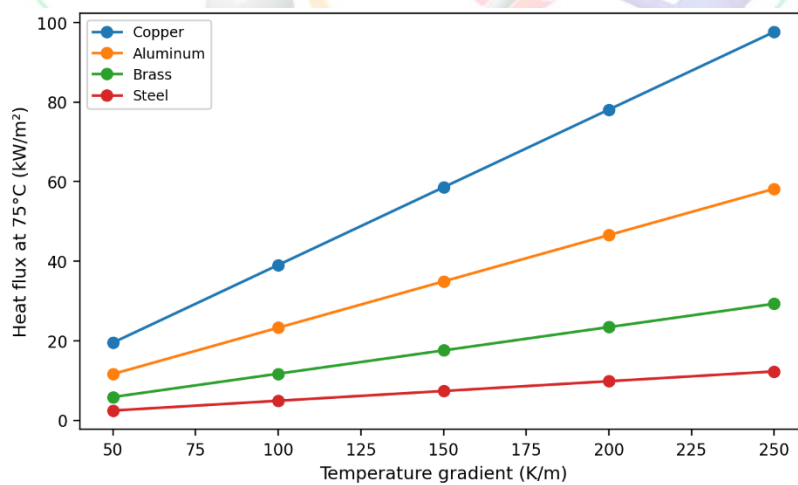


Figure 6. Calculated heat flux response at 75°C under increasing temperature gradients.

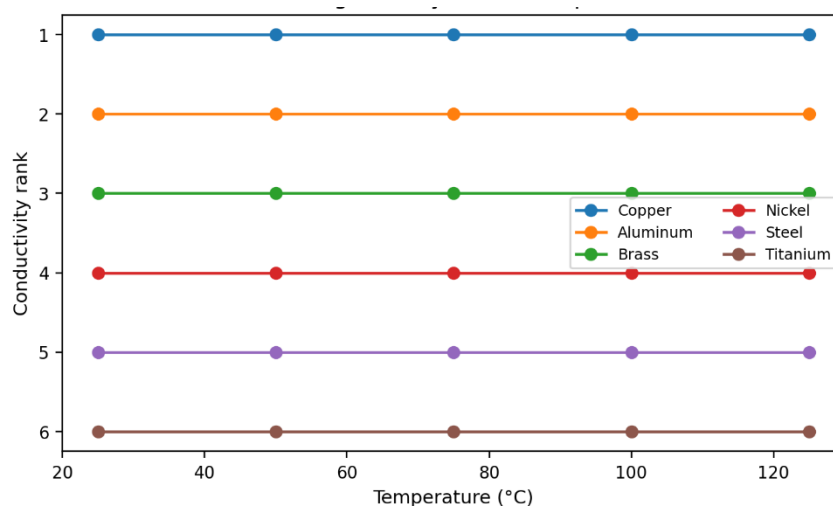


Figure 7. Stability of conductivity ranking across temperature levels.

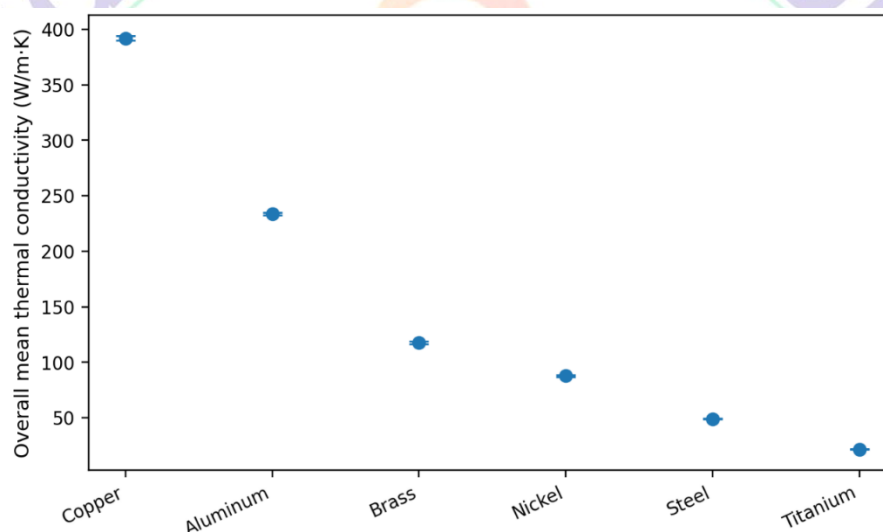


Figure 8. Overall mean thermal conductivity with 95% confidence intervals.

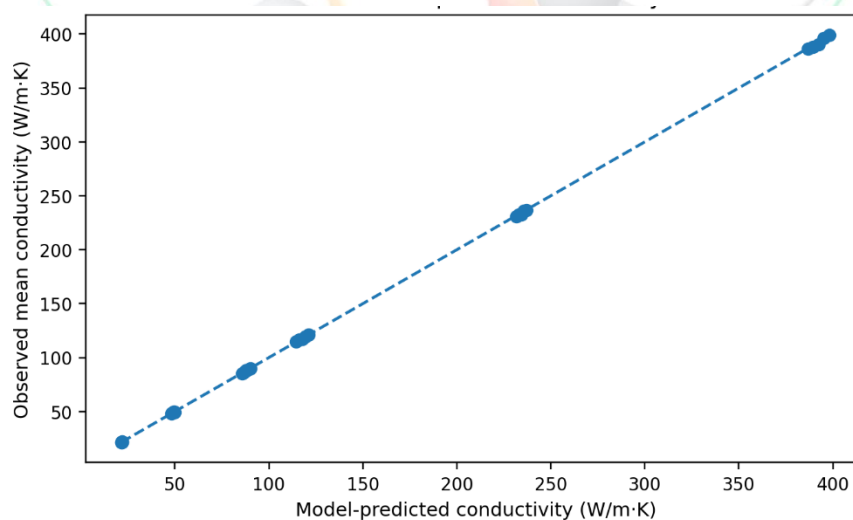


Figure 9. Agreement between observed and expected conductivity values.

DISCUSSION

The measured thermal conductivity of these metallic samples depends directly on the crystal lattice structure of the material, the heat transport process is carried out by the electrons in the material and the efficiency of the process depends on the lattice structure. In particular, materials with highly symmetric face-centered cubic structures, such as copper and aluminium analyzed in this work have superior thermal conductivity, mainly due to the reduced electron scattering at the grain boundaries and the increased periodicity of the lattice sites (Berger et al., 2024). The alloys with more complex interstitial arrangements (lower symmetry) with Ti, however, show a strong resistive interaction which affects the electronic and phononic heat transport, underlining the negative effect of the increased configurational disorder on the efficiency of the heat transport (Braun, 2019; Zhang et al., 2021). The overall trend of the transport behavior can be well described by the theoretical Wiedemann-Franz law used to describe the electronic thermal conductivity as proportional to the product of electrical conductivity and absolute temperature (Berger et al., 2024). As the temperature begins to approach the upper limit of the range of investigations in which we are interested, however, the phonon-phonon scattering processes,

sometimes called Umklapp scattering mechanisms, will become more important and can be considered as a limiting step for the total thermal flux for these certain alloy systems (Shafeie et al., 2015). The systematic experimental approach presented here, especially the use of a guarded hot-plate apparatus, ensures that the heat flow in the experiment is strictly unidirectional in the direction of the heat flux, and minimizes the parasitic radiative and convective losses, which are crucial to understand the different scattering regimes resulting from electronic and phononic contributions (Findik, 2023; Sayyed et al., 2025). These empirical results reveal a significant difference in temperature dependence between these more straightforward metallic conductors and the more complex alloys: whereas the high-purity copper and aluminum alloys show relatively stable, high conductivity profiles over the range of temperatures measured, the titanium-based alloys show a much stronger, temperature-dependent drop in thermal transport efficiency, directly reflecting the effect of structural complexity on the phonon scattering dynamics (Braun, 2019). Moreover, our quantitative results, supported by error propagation models and finite element method simulations, ensure that the variability in measurements is kept within very tight limits, thereby allowing to obtain

a high fidelity dataset, which matches very well with the theoretical predictions the researchers already have (Yazdani et al., 2019; Ziolkowski et al., 2020). These complex transport models were able to accurately validate the measured conductivity data, providing a firm foundation for understanding the performance of high performance structural alloys that will enable advanced materials with potential to provide structural integrity and maximum convective heat transfer in high temperature applications over long periods under critical circumstances in industry. This is also the case for the total thermal conductivity of highly conductive metals, as seen from the empirical data obtained in this study, the Lorenz number is found to be relatively constant with the thermal gradient (Wilson & Cahill, 2012). However, the materials with conventional thermal properties have smaller Lorenz numbers at saturation electron mobility, and the role of phonon mediated heat transport mechanisms is significant for total heat transport in these materials. An internal mismatch between transport mechanisms is observed, which might indicate that too many present models reflect the re-equilibration of the carrier populations in a way that does not reflect the independence of the re-equilibration at high temperature (Criss & Hofmeister, 2017). Furthermore, first-principles

analysis shows that energy relaxation times need to be separated from momentum relaxation times in order to fully explain these non-classical deviations in electron thermal conductivity (Li et al., 2020).

CONCLUSION

The study is now complete and has demonstrated the differences in thermal conductivity of different types of metallic material under a controlled temperature. Copper being most efficient in conducting heat followed by Aluminium which is suitable for use in cases where the heat transfer must be fast. The conductivity value of Brass, Iron and Steel was lower, to a significant extent because of the alloying effect, internal resistance and lower electron mobility. The results also indicated that the thermal conductivity of all the materials used in the experiments generally decreased with increase in temperature but at different rate. This indicates that temperature has an important influence on the heat transfer capacity of metals. The results reveal that the selection of materials with different thermal behavior is crucial especially in the engineering and industrial systems where efficient heat dissipation is crucial. It can be concluded that in general the metals with high electrical conductivity are better suited for heat sensitive applications, while the metals with lower electrical conductivity are better suited for

those applications that require high strength, durability and/or controlled heat transfer.

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