

COMPARISON OF HEAT TRANSFER RATES IN DIFFERENT METALS: A COMPREHENSIVE ANALYSIS

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Abstract: The thermal conductivity of metals represents a fundamental property that governs heat transfer efficiency in numerous engineering applications. This research paper presents a comprehensive analysis of heat transfer rates in different metals, examining the underlying physical mechanisms, experimental methodologies, and practical implications of thermal conductivity variations. Through systematic comparison of common metals including copper, aluminum, steel, iron, silver, and their alloys, this study elucidates the factors influencing thermal transport properties and their applications in thermal management systems. The analysis incorporates both theoretical foundations and experimental data to provide insights into material selection criteria for various thermal applications. Results demonstrate significant variations in thermal conductivity among different metals, with copper and silver exhibiting the highest values, while stainless steel and other alloys showing considerably lower thermal transport capabilities. This comprehensive examination contributes to the understanding of metallic thermal properties and provides practical guidance for materials selection in thermal engineering applications.

Index Terms: Thermal conductivity, heat transfer, metals, thermal properties, materials engineering, thermal management

I. INTRODUCTION

Heat transfer in metals represents one of the most fundamental phenomena in materials science and engineering, influencing applications ranging from electronic cooling systems to industrial heat exchangers. The ability of metals to conduct thermal energy efficiently stems from their unique electronic structure, which provides free electrons capable of rapid energy transport throughout the material matrix. Understanding the comparative heat transfer characteristics of different metals is essential for optimal material selection in thermal management applications, where efficiency, cost, and performance requirements must be carefully balanced.

The significance of metallic thermal conductivity extends far beyond academic interest, encompassing critical applications in aerospace, automotive, electronics, and energy systems. Modern technological advancement increasingly demands materials with superior thermal transport properties, driving research into both fundamental mechanisms and practical applications of metallic heat transfer. The relationship between atomic structure, electronic properties, and thermal conductivity provides insights into material behavior that inform both theoretical understanding and practical engineering decisions.

Historical development of thermal conductivity research in metals dates back to the early 19th century, when pioneers like Jean Baptiste Joseph Fourier established fundamental principles of heat conduction. The subsequent development of kinetic theory and electronic band theory provided theoretical frameworks for understanding thermal transport in metallic systems. The Wiedemann-Franz law, established in the 1850s, demonstrated the fundamental relationship between electrical and thermal conductivity in metals, providing a cornerstone for modern understanding of thermal transport mechanisms.

Experimental techniques for measuring thermal conductivity have evolved significantly, from early steady-state methods to sophisticated transient techniques capable of measuring temperature-dependent properties across wide ranges. Modern measurement methods include guarded hot plate techniques, flash diffusivity methods, and laser-based transient techniques that provide accurate thermal property data under various conditions. These advances have enabled precise characterization of thermal properties across different temperature ranges and material compositions.

The practical importance of thermal conductivity variations among metals cannot be overstated in contemporary engineering applications. Electronic devices require efficient heat dissipation to maintain optimal performance and reliability, while energy systems depend on thermal management for efficiency optimization. Heat exchangers, thermal interface materials, and cooling systems all rely on careful selection of metals with appropriate thermal transport properties to achieve desired performance characteristics.

Theoretical understanding of thermal conduction in metals is based on the electronic contribution to heat transport, which dominates thermal conductivity in most metallic systems. The free electron model provides a fundamental framework for understanding thermal transport, while more sophisticated band theory approaches offer detailed insights into the relationship between electronic structure and thermal properties. These theoretical foundations enable prediction of thermal behavior and guide material development efforts.

Contemporary research directions in metallic thermal conductivity encompass both fundamental studies of thermal transport mechanisms and applied research focused on specific applications. Nanostructured materials, composite systems, and novel alloys represent active areas of investigation, while computational approaches provide new tools for understanding and predicting thermal behavior. The integration of theoretical, experimental, and computational approaches continues to advance understanding of thermal transport in metallic systems.

The scope of this research encompasses systematic comparison of thermal conductivity values, examination of underlying physical mechanisms, analysis of temperature dependence, and evaluation of practical implications for engineering applications. Through comprehensive analysis of different metals and their thermal transport properties, this study aims to provide valuable insights for materials selection and thermal system design in various technological applications.

II. THEORETICAL FOUNDATIONS

The theoretical understanding of heat transfer in metals is fundamentally rooted in the electronic theory of solids, which explains thermal conduction primarily through the motion of free electrons. In metallic systems, thermal energy is transported by electrons moving through the crystal lattice, with phonon contributions typically being secondary except at very high temperatures. The electronic contribution to thermal conductivity is described by the Wiedemann-Franz law, which establishes a direct relationship between thermal and electrical conductivity through the Lorenz number.

The classical free electron model provides the foundation for understanding thermal transport in metals, treating conduction electrons as a free electron gas that moves through the periodic potential of the crystal lattice. According to this model, thermal conductivity is proportional to the product of electronic specific heat, electron velocity, and mean free path. The electronic specific heat varies linearly with temperature at moderate temperatures, while the mean free path is influenced by scattering mechanisms including impurities, grain boundaries, and phonon interactions.

The kinetic theory approach to thermal conduction yields the expression $\kappa = (1/3)Cv\Lambda$, where κ is thermal conductivity, C is specific heat per unit volume, v is average particle velocity, and Λ is the mean free path. For metals, this relationship is modified to account for the electronic nature of heat transport, leading to the Drude model expression for thermal conductivity. The Drude model successfully explains many aspects of metallic thermal behavior, including the temperature dependence and the relationship between thermal and electrical properties.

Quantum mechanical treatments of thermal conduction provide more sophisticated understanding of transport phenomena in metals. The Sommerfeld model incorporates Fermi-Dirac statistics and quantum mechanical considerations, leading to improved predictions of thermal behavior at low temperatures. Band theory approaches consider the detailed electronic structure of metals, providing insights into the effects of alloying, crystal structure, and electronic band filling on thermal transport properties.

The Wiedemann-Franz law, expressed as $\kappa/\sigma T = L_0$, where σ is electrical conductivity, T is absolute temperature, and L_0 is the Lorenz number ($2.45 \times 10^{-8} \text{ W} \cdot \Omega \cdot \text{K}^{-2}$), represents one of the most important relationships in metallic thermal transport. This law holds remarkably well for pure metals at moderate temperatures, but deviations occur in alloys, at very high or low temperatures, and in materials with complex electronic structures. Understanding these deviations provides insights into the underlying transport mechanisms and material properties.

Scattering mechanisms play crucial roles in determining thermal conductivity values in metals. Electron-phonon scattering, which increases with temperature, typically dominates thermal resistance in pure metals at elevated temperatures. Impurity scattering, largely temperature-independent, becomes significant in alloys and impure metals. Grain boundary scattering affects thermal conductivity in polycrystalline materials, while surface scattering can influence thermal properties in thin films and nanostructured materials.

The temperature dependence of thermal conductivity in metals reflects the interplay between various scattering mechanisms and electronic properties. At low temperatures, thermal conductivity typically increases with temperature due to increasing electronic specific heat. At intermediate temperatures, thermal conductivity often reaches a maximum before decreasing due to increased phonon scattering. At high temperatures, thermal conductivity generally decreases with increasing temperature following the Wiedemann-Franz relationship.

Alloying effects on thermal conductivity arise from multiple mechanisms, including increased electron scattering due to compositional disorder, changes in electronic structure, and formation of secondary phases. Solid solution alloys typically exhibit reduced thermal conductivity compared to pure metals due to additional scattering from compositional fluctuations. Precipitation-hardened alloys may show complex thermal behavior depending on precipitate size, distribution, and thermal properties.

III. EXPERIMENTAL METHODS AND MEASUREMENT TECHNIQUES

Accurate measurement of thermal conductivity in metals requires sophisticated experimental techniques that can account for the high thermal transport rates characteristic of metallic materials. The choice of measurement method depends on factors including temperature range, sample geometry, expected thermal conductivity values, and required accuracy. Steady-state methods provide direct measurement of thermal conductivity under equilibrium conditions, while transient techniques offer advantages in measurement speed and temperature range capability.

The guarded hot plate method represents one of the most accurate steady-state techniques for measuring thermal conductivity in metals. This method involves placing the sample between heated and cooled plates while maintaining one-dimensional heat flow through careful guarding against lateral heat losses. Temperature measurements at known positions within the sample, combined with heat flux measurements, allow direct calculation of thermal conductivity using Fourier's law. The method requires careful attention to contact resistance, heat losses, and temperature uniformity to achieve accurate results.

Comparative methods, including the divided bar technique, provide alternative approaches for thermal conductivity measurement by comparing unknown samples with reference materials of known thermal properties. These methods can offer improved accuracy by eliminating some systematic errors associated with absolute measurements. The divided bar method involves placing the sample in series with reference materials and measuring temperature distributions under steady-state conditions. Proper selection of reference materials and careful attention to thermal contact resistance are essential for accurate results.

Flash diffusivity methods have become increasingly popular for thermal conductivity measurements due to their speed and versatility. These transient techniques involve applying a brief heat pulse to one surface of the sample while monitoring temperature response on the opposite surface. Thermal diffusivity is calculated from the temperature rise characteristics, and thermal conductivity is obtained by multiplying thermal diffusivity by density and specific heat. The method requires careful attention to heat losses, sample preparation, and data analysis to achieve accurate results.

Laser-based measurement techniques offer advantages for high-temperature measurements and small sample sizes. Laser flash methods provide rapid heating and precise temperature monitoring, enabling measurements across wide temperature ranges. Modulated laser techniques can provide frequency-dependent thermal property measurements, offering insights into thermal transport mechanisms. These methods require sophisticated instrumentation and careful calibration but can provide highly accurate results under challenging conditions.

Hot wire methods involve placing a thin wire or film heater within or on the sample surface and monitoring temperature response to controlled heating. These methods can provide rapid measurements and are particularly useful for high thermal conductivity materials where other methods may be challenging. The technique requires careful analysis of heat transfer geometry and consideration of contact resistance effects to achieve accurate results.

Sample preparation plays a critical role in thermal conductivity measurements, with surface finish, sample geometry, and thermal contact conditions significantly affecting results. Samples must be prepared with parallel surfaces, appropriate dimensions, and clean interfaces to ensure accurate measurements. Thermal interface materials may be required to minimize contact resistance, but their properties must be carefully characterized to avoid measurement errors.

Temperature measurement accuracy directly impacts thermal conductivity determination, requiring precise thermometry and careful calibration procedures. Thermocouple selection, placement, and calibration must be appropriate for the temperature range and material properties being investigated. Radiation losses and thermal contact effects must be minimized through proper experimental design and measurement procedures.

IV. COMPARATIVE ANALYSIS OF THERMAL CONDUCTIVITY

The thermal conductivity values of different metals span several orders of magnitude, reflecting fundamental differences in electronic structure, crystal structure, and atomic arrangements. This wide variation in thermal transport properties provides opportunities for material selection based on specific application requirements, from high-performance thermal management to thermal insulation applications. Understanding

these variations and their underlying causes is essential for effective materials selection and thermal system design.

Pure metals generally exhibit the highest thermal conductivity values, with copper and silver leading the list at approximately 401 and 429 W/m·K respectively at room temperature. These exceptional thermal transport properties result from high concentrations of free electrons and minimal scattering mechanisms in the pure metal lattice. Gold, with a thermal conductivity of approximately 317 W/m·K, also exhibits excellent thermal properties, making it valuable for specialized applications despite its high cost.

Aluminum represents an important category of thermally conductive metals, with pure aluminum exhibiting thermal conductivity of approximately 237 W/m·K. Despite being lower than copper, aluminum's thermal properties, combined with its low density and corrosion resistance, make it attractive for many thermal management applications. The thermal conductivity-to-weight ratio of aluminum is particularly favorable in applications where weight considerations are important.

Table 4.1: Comparative Analysis of Thermal Conductivity

Metal/Alloy	Thermal Conductivity (W/m·K)	Density (g/cm ³)	Specific Heat (J/g·K)	Thermal Diffusivity (mm ² /s)	Applications
Silver	429	10.49	0.235	174	Electrical contacts, heat sinks
Copper	401	8.96	0.385	117	Heat exchangers, electronics
Gold	317	19.32	0.129	127	Specialized electronics
Aluminum	237	2.70	0.897	97	Automotive, aerospace
Zinc	116	7.14	0.388	42	Coatings, alloys
Iron	80	7.87	0.449	23	Structural applications
Nickel	91	8.90	0.444	23	Superalloys, catalysts
Stainless Steel 304	16	8.00	0.500	4	Corrosion-resistant structures
Carbon Steel	50	7.85	0.490	13	General construction
Titanium	22	4.51	0.523	9	Aerospace, biomedical

Iron and steel represent moderate thermal conductivity materials, with pure iron exhibiting thermal conductivity of approximately 80 W/m·K. Carbon steels typically show thermal conductivity values in the range of 40-60 W/m·K, depending on carbon content and microstructure. The relatively moderate thermal conductivity of steels, combined with their mechanical properties and cost-effectiveness, makes them suitable for structural applications where thermal properties are secondary considerations.

Stainless steels exhibit significantly reduced thermal conductivity compared to carbon steels, with typical values ranging from 12-20 W/m·K depending on composition and microstructure. The addition of chromium, nickel, and other alloying elements creates additional scattering mechanisms that reduce thermal transport efficiency. However, the corrosion resistance and mechanical properties of stainless steels often outweigh thermal considerations in many applications.

Aluminum alloys show thermal conductivity values that are generally lower than pure aluminum, with typical ranges from 120-200 W/m·K depending on alloy composition and heat treatment. The 6000 series aluminum alloys, commonly used in structural applications, exhibit thermal conductivity values around 150-180 W/m·K. The 2000 and 7000 series alloys, designed for high strength applications, typically show lower thermal conductivity due to higher alloying content.

Copper alloys demonstrate how alloying can significantly reduce thermal conductivity while providing other beneficial properties. Brass alloys typically exhibit thermal conductivity values in the range of 100-150 W/m·K, while bronze alloys may show values from 25-60 W/m·K depending on composition. These reductions in thermal conductivity result from increased electron scattering due to compositional disorder and secondary phase formation.

The temperature dependence of thermal conductivity varies significantly among different metals, with pure metals generally showing decreasing thermal conductivity with increasing temperature above room temperature. This behavior reflects increased electron-phonon scattering at higher temperatures. Alloys may show different temperature dependencies due to competing effects of temperature on various scattering mechanisms and electronic properties.

V. FACTORS AFFECTING HEAT TRANSFER RATES

Multiple factors influence heat transfer rates in metals, ranging from intrinsic material properties to external conditions and microstructural characteristics. Understanding these factors is essential for predicting thermal behavior, optimizing material selection, and designing effective thermal management systems. The complex interplay between these factors determines the overall thermal performance of metallic systems in practical applications.

Temperature represents one of the most significant factors affecting thermal conductivity in metals, with effects varying depending on the dominant heat transfer mechanisms and material characteristics. In pure metals, thermal conductivity typically decreases with increasing temperature above room temperature due to enhanced electron-phonon scattering. The temperature coefficient of thermal conductivity can be substantial, with some metals showing 50% or greater reductions in thermal conductivity between room temperature and 500°C.

Alloy composition profoundly affects thermal conductivity through multiple mechanisms including increased electron scattering, changes in electronic structure, and formation of secondary phases. Solid solution strengthening, achieved by adding alloying elements, typically reduces thermal conductivity proportionally to the square of the concentration difference between solute and solvent atoms. This relationship, known as Nordheim's rule, provides a framework for understanding thermal property changes in alloy systems.

Microstructural features including grain size, grain boundaries, and crystallographic texture significantly influence thermal transport properties. Grain boundaries act as scattering centers for heat-carrying electrons, with effects becoming more pronounced as grain size decreases. Nanocrystalline materials may exhibit substantially reduced thermal conductivity compared to coarse-grained counterparts due to enhanced grain boundary scattering. The relationship between grain size and thermal conductivity generally follows inverse proportionality for grain sizes below approximately 100 micrometers.

Impurity content and defect density play crucial roles in determining thermal conductivity values, with even small concentrations of impurities potentially causing significant reductions in thermal transport. Point defects, including vacancies and interstitial atoms, scatter heat-carrying electrons and reduce thermal conductivity. Dislocation density, influenced by mechanical processing and thermal treatment, affects thermal properties through strain field interactions with conduction electrons.

Phase transformations and precipitation reactions can dramatically alter thermal conductivity by changing the microstructure and introducing new scattering mechanisms. Age-hardening aluminum alloys, for example, show significant changes in thermal conductivity during precipitation processes. The size, distribution, and coherency of precipitates all influence thermal transport properties, with coherent precipitates typically having less impact than incoherent interfaces.

Surface conditions and oxidation can affect thermal conductivity measurements and practical thermal performance. Oxide layers, while often thin, can significantly impact thermal contact resistance and apparent thermal conductivity in systems where interface effects are important. Surface roughness affects thermal contact resistance and may influence thermal property measurements, particularly in thin samples or systems with multiple interfaces.

Mechanical stress and deformation affect thermal conductivity through their influence on crystal structure and defect density. Elastic stress can modify electronic band structure and affect thermal transport, while plastic deformation introduces dislocations and other defects that increase thermal resistance. The relationship between stress and thermal conductivity is complex and depends on the specific loading conditions and material characteristics.

Processing history significantly influences thermal properties through its effects on microstructure, defect density, and residual stress. Cold working typically reduces thermal conductivity by introducing dislocations and residual stress, while annealing treatments can restore thermal properties by reducing defect density and

relieving stress. Heat treatment conditions, including heating rate, maximum temperature, and cooling rate, all affect final thermal properties through their influence on microstructural evolution.

VI. APPLICATIONS AND PRACTICAL IMPLICATIONS

The practical applications of metals with different thermal conductivity values span virtually every sector of modern technology, from microelectronics to large-scale energy systems. Understanding the relationship between thermal properties and application requirements is essential for optimal material selection and system design. The economic, performance, and reliability implications of thermal conductivity variations make this knowledge crucial for engineers and designers across multiple disciplines.

Electronic cooling applications represent one of the most demanding areas for thermal management, where high thermal conductivity materials are essential for removing heat from semiconductor devices and preventing thermal failure. Copper and aluminum are widely used in heat sinks, thermal interface materials, and heat spreaders due to their excellent thermal properties and reasonable cost. The trend toward higher power densities in electronics continues to drive demand for materials with superior thermal transport properties.

Heat exchanger design relies heavily on thermal conductivity considerations, with material selection significantly affecting heat transfer efficiency and system performance. Copper and copper alloys are commonly used in high-performance heat exchangers due to their excellent thermal properties, while aluminum alloys are preferred in weight-sensitive applications. The choice between materials involves balancing thermal performance, corrosion resistance, mechanical properties, and cost considerations.

Automotive applications increasingly require effective thermal management for both traditional and electric vehicle systems. Engine cooling systems, exhaust heat recovery, and battery thermal management all depend on careful selection of materials with appropriate thermal properties. Aluminum alloys have become dominant in automotive heat exchangers due to their favorable combination of thermal conductivity, weight, and corrosion resistance.

Aerospace applications demand materials that provide excellent thermal performance while meeting stringent weight, reliability, and environmental requirements. High thermal conductivity materials are essential for thermal protection systems, electronic cooling, and structural applications where thermal expansion must be controlled. The extreme operating conditions in aerospace applications require careful consideration of temperature-dependent thermal properties and long-term stability.

Building and construction applications utilize thermal properties for both energy efficiency and structural performance. Metals with high thermal conductivity are used in heating and cooling systems, while materials with lower thermal conductivity may be preferred for structural applications where thermal bridging must be minimized. The growing emphasis on energy-efficient buildings continues to drive interest in materials with tailored thermal properties.

Industrial process equipment relies on thermal conductivity for heat transfer efficiency and process control. Metals with high thermal conductivity are essential for heat exchangers, boilers, and other heat transfer equipment, while materials with lower thermal conductivity may be preferred for insulation and thermal barrier applications. The harsh operating conditions in many industrial processes require materials that maintain thermal properties while resisting corrosion and mechanical degradation.

Power generation systems, including both conventional and renewable energy technologies, require materials with specific thermal properties for optimal performance. Thermal power plants utilize high thermal conductivity materials in heat exchangers and cooling systems, while nuclear applications require materials that maintain thermal properties under radiation exposure. Solar energy systems require materials with appropriate thermal properties for efficient energy collection and transfer.

The economic implications of thermal conductivity variations are substantial, affecting both initial material costs and long-term operational expenses. High thermal conductivity materials like copper and silver command premium prices but may provide superior performance that justifies higher costs. The total cost of ownership, including initial material costs, fabrication expenses, and operational efficiency, must be considered in material selection decisions for thermal applications.

VII. CONCLUSION

This comprehensive analysis of heat transfer rates in different metals reveals the fundamental importance of thermal conductivity in determining material performance across a wide range of applications. The systematic comparison of thermal properties demonstrates that metals exhibit a broad spectrum of thermal conductivity values, from the exceptional performance of silver and copper to the moderate thermal transport properties of steels and other alloys. These variations reflect underlying differences in electronic structure, crystal structure, and microstructural characteristics that govern thermal transport mechanisms.

The theoretical foundations of thermal conduction in metals, rooted in electronic transport theory and the Wiedemann-Franz law, provide essential frameworks for understanding and predicting thermal behavior. The dominance of electronic contributions to thermal conductivity in most metals explains both the high thermal conductivity values and the relationship between thermal and electrical properties. Understanding these fundamental mechanisms enables informed material selection and system design for thermal applications.

Experimental methods for measuring thermal conductivity have evolved to provide accurate and reliable data across wide temperature ranges and diverse material types. The availability of multiple measurement techniques, from steady-state methods to transient approaches, enables comprehensive characterization of thermal properties under various conditions. Continued advances in measurement technology promise even greater accuracy and expanded capability for thermal property determination.

The comparative analysis reveals that material selection for thermal applications requires careful consideration of multiple factors beyond thermal conductivity alone. The combination of thermal properties with mechanical performance, corrosion resistance, cost, and processability determines the optimal choice for specific applications. The comprehensive property data presented in this study provides a foundation for informed material selection decisions.

The factors affecting heat transfer rates in metals are complex and interconnected, requiring sophisticated understanding for optimal material utilization. Temperature effects, alloy composition, microstructural characteristics, and processing history all influence thermal properties in ways that must be considered in both material development and application design. The interplay between these factors creates opportunities for tailoring thermal properties through careful material design and processing.

The practical applications of metals with different thermal conductivity values demonstrate the broad impact of thermal properties on technological advancement. From microelectronics to large-scale energy systems, thermal management continues to be a critical factor in system performance and reliability. The ongoing development of new technologies and increasing performance demands will continue to drive research and development in metallic thermal properties.

Future research directions in metallic thermal conductivity will likely focus on nanostructured materials, advanced alloys, and novel processing techniques that can enhance thermal properties while maintaining other desirable characteristics. Computational approaches, combined with advanced experimental techniques, offer new opportunities for understanding and predicting thermal behavior in complex material systems.

The economic and environmental implications of thermal conductivity variations will become increasingly important as energy efficiency and sustainability concerns grow. Materials with optimized thermal properties can contribute to energy savings, reduced environmental impact, and improved system performance across multiple applications. The continued development and application of high thermal conductivity materials will play important roles in addressing global energy and environmental challenges.

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