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Size-Dependent Thermal Diffusivity of Selected Metallic Nanostructures for Grain size

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Highlights

- Six metallic nanomaterials are compared through one common theoretical approach.
- Thermal diffusivity connects conductivity, density, and heat capacity directly.
- Conductivity produces the strongest change in nanoscale thermal diffusivity.
- Aluminium showed the highest modelled nanoscale diffusivity.

Abstract

This study examines thermal behaviour of six selected nanoscale metallic materials. The selected metals include Ag, Cu, Al, Au, Fe, and Ni. Particle diameters between one and fifteen nanometres are considered systematically. The same theoretical method is applied to every selected metal. Thermal conductivity, density, and heat capacity are treated as size-dependent properties. Thermal diffusivity is calculated through their established mathematical relationship. The results show clear thermal changes with decreasing particle diameter. Thermal conductivity produces the strongest change in calculated thermal diffusivity. Density shows a smaller contribution across the selected particle-size range. Heat capacity provides an additional influence through thermal energy storage.

The largest relative changes appear below approximately five nanometres. Surface atoms and boundary scattering become more important within this region. Thermal properties gradually approach corresponding bulk values at larger diameters. Silver and copper maintain comparatively stronger heat-spreading behaviour among metals. Aluminium provides a useful balance between density and thermal performance. Gold, iron, and nickel show their own size-dependent thermal responses. The study provides one common comparison for six important metallic nanomaterials. Its findings may support particle selection for nanoscale thermal-management applications.

Keywords: Metallic nanoparticles, thermal diffusivity, thermal conductivity, density, heat capacity, particle size.

I. INTRODUCTION

A. Thermal Behaviour of Metals at the Nanoscale

Metallic materials alter thermally as particle size decreases. When dimensions approach nanometres, these changes intensify. Bulk materials have fewer surface atoms than smaller particles. Nanoparticle surface atoms have poorer bonding and varied local environments. Their enhanced contribution alters metal heat storage and transport. Nanoscale metals act differently from bulk metals [1]. Metals transmit heat via electrons and lattice vibrations. Electrons transport most heat in pure metals. Electrons interact with lattice vibrations during heat transport. Small barriers limit carriers and promote dispersion [2].

This constraint reduces heat conductivity at smaller particle sizes. Heat movement is further reduced by grain boundaries and surface imperfections [3]. Under typical bulk circumstances, silver and copper transmit heat well. Smaller structures have higher boundary and surface scattering. Gold conductivity varies with microscopic particle sizes. Conductivity and heat capacity vary with aluminium nanoparticles. The magnetic properties of iron and nickel add effects. Thus, each metal has a unique nanoscale heat response. Particle form also affects thermophysical characteristics. Nanoparticles limit heat transporters in three dimensions. Nanowires are simpler to manipulate lengthwise than diameter wise. Thin coatings impede heat mobility mostly via thickness. Particle size is the common factor among forms [4].

Nanoscale materials vary specific heat. Surface vibrations promote tiny particle thermal energy storage. This phenomenon is especially apparent at extremely tiny particle sizes [5-7]. Also, surface relaxation and lattice contraction may vary density. Its fluctuation is less than conductivity variations in many metallic systems. Material thermal diffusivity is directly affected by density.

B. Importance of Thermal Diffusivity in Nanoscale Heat Transfer

Thermal diffusivity measures heat transfer through any medium. It reflects how rapidly that material balances temperature differences. High values indicate rapid heat diffusion following thermal disturbance. Lower values indicate slower material temperature adjustment. Conductivity, density, and specific heat determine thermal diffusivity. Thermal diffusivity depends upon conductivity, density, and specific heat together. Its established relation is expressed through the following mathematical formulation:

$$\alpha(D,T) = \frac{k(D,T)}{\rho(D)C_p(D,T)} \qquad (1)$$

Where, $\alpha(D,T)$ is the thermal diffusivity at size D and temperature T, $k(D,T)$ is the size-dependent thermal conductivity of the material, $\rho(D)$ is the its density at the selected particle size, $C_p(D,T)$ is the heat capacity under constant pressure conditions.

Equation (1) connects four thermal characteristics. This standard relation includes thermal conductivity in the numerator. Thus, conductivity increases thermal diffusivity. The denominator includes density and heat capacity. Increased thermal diffusivity usually decreases. Conductivity determines how well heat travels through the metal. A volume's density describes its material bulk. Heat capacity is the energy required to heat material. One relevant thermal measure is thermal diffusivity. Thermal transfer at nanoscale varies from bulk heat conduction [2]. Short dimensions enhance dispersion and reduce heat-carrier transit. Cahill et al. explored these crucial nanoscale transport modifications [2]. Ju et al. found size-dependent diffusivity in multilayered films [8]. Recent research supports diffusivity measurements in tiny one-dimensional objects [9]. Small thermal devices and nanoelectronics employ thermal diffusivity. Fast heat spreading shields sensitive sections from local temperature rise. Device functioning may cause undesired thermal areas due to slow heat dispersion. Thus, metallic materials enable safer nanoscale gadget performance.

The actual result depends upon their combined size-dependent changes. This combined effect requires calculation at every selected particle size.

C. Research Gap and Need for the Present Study

Nanomaterial thermal characteristics are explained in several papers [1]. Many studies focus on conductivity, heat capacity, or Debye temperature. Other research examines melting temperature and thermodynamic factors [5]. These contributions provide the groundwork for comparative research. Kumar and Singh examined grain-size effects on nano-thermal conductivity [3]. Both Rawat and Goyal evaluated particular heat and conductivity changes [5]. Jaiswal and Pandey modelled metallic nanoparticle characteristics [4]. Singh et al. examined Ni, Al, and Cu nanosolids [7]. This research shows important property changes with smaller materials.

Size-dependent thermal diffusivity has been studied experimentally. Diffusion in thin multilayered materials was studied by Ju et al. [8]. Diffusion in one-dimensional nanoscale structures was examined by Karamati et al. [9]. These pieces have diverse materials, construction, and sizes. Their studies cannot compare six metals directly.

Similar comparisons of Ag, Cu, Al, Au, Fe, and Ni are helpful. These metals vary in density, conductivity, heat capacity, and atomic bonding. Compare them to see which attribute influences diffusivity more. It can demonstrate whether all metals have comparable size patterns. One to fifteen nanometres require rigorous study. Surface impacts are substantial in this nanoscale area. Large changes below five nanometres may be noticed. Values may eventually approach bulk behaviour at bigger dimensions. Previous studies addressed one attribute using distinct theoretical formulations. This research links three attributes using a diffusivity relation. The size range is the same for each metal. Common calculating processes are used for a fair comparison.

D. Aim and Objectives of the Study

The specific objectives of this investigation are stated below:

1. To calculate thermal properties of selected metals from 1–15 nm.
2. To determine thermal diffusivity using the established relation.
3. To compare nanoscale results with corresponding bulk values.

It predicts larger diffusivity changes at extremely tiny scales. Conductivity lowering may boost these changes most. Some density changes have a lesser but detectable numerical impact. Heat-capacity variations may affect metal energy storage. Together, the findings will clarify nanoscale heat movement.

II. THEORETICAL BACKGROUND

A. Basic Relation for Thermal Diffusivity

How quickly heat spreads through a material is thermal diffusivity. One physical quantity combines thermal conduction and thermal storage. The value relies on conductivity, density, and specific heat capacity. Calculated thermal diffusivity is related to thermal conductivity. The connection between density and specific heat capacity is inverse. Thus, any size dependent modification affects diffusivity. More conductivity means faster heat spreading in metals.

Materials with higher heat capacities store more thermal energy. High density increases material mass per volume. Storage factors usually lower thermal diffusivity. The connection applies to bulk and nanoscale materials. In the nanoscale, each input property is size-dependent. Nanoscale heat transport is strongly surface and boundary-driven [1, 2]. All smaller particles cannot be adequately represented by bulk input values.

A normalized diffusivity ratio can support comparison among selected metals:

$$\alpha_r(D_m, T) = \frac{\alpha(D_m, T)}{\alpha(\infty, T)} \qquad (2)$$

Here, $\alpha(\infty, T)$represents the corresponding bulk thermal diffusivity value.

An almost-unity ratio indicates bulk material behaviour. A lower ratio suggests higher nanoscale diffusivity decrease. This method standardizes metal comparisons.

B. Size-Dependent Thermal Conductivity

A material's thermal conductivity assesses its energy transmission. Because electrons travel freely, bulk metals conduct well. Metallic structures also conduct thermal energy via lattice vibrations. Both contributions are limited by tiny particle sizes. Thermal electrons are disrupted by metallic barriers. They disperse lattice vibrations via the smaller particle. With decreasing particle size, effective thermal conductivity decreases. This decrease increases as dimensions approach carrier travel distances [2].

Several nanoscale heat transfer processes were described by Cahill et al. [2]. They clearly described boundary scattering and short heat-carrier movement. Kumar and Singh found nanomaterial conductivity varied with grain size [3]. Their findings suggest lower conductivity at smaller grain sizes.

Rawat and Goyal examined modest material conductivity variations [5]. Smaller gold particles change conductivity [6]. Nickel, aluminium, and copper have size-dependent thermal behaviour [7]. Different atomic bonding makes each metal react differently. Conductivity also depends on electron concentration and lattice structure.

For metallic particles, total conductivity may contain two main contributions:

$$k(D_m, T) = k_e(D_m, T) + k_l(D_m, T) \quad (3)$$

Where, $k_e(D_m, T)$ is the electronic thermal conductivity contribution and $k_l(D_m, T)$ is the lattice conductivity contribution.

Electron contribution is frequently higher in highly conductive pure metals. Nanoscale scattering lowers both thermal conductivity contributions. Normalized conductivity ratios enable bulk behaviour comparisons.

A normalized conductivity ratio supports comparison with corresponding bulk behaviour:

$$k_r(D_m, T) = \frac{k(D_m, T)}{k(\infty, T)} \quad (4)$$

The ratio approaches unity as nanoscale conductivity approaches bulk conductivity. Particle structure conductivity reduction is stronger with smaller ratios. This comparison works for metals with various bulk conductivities.

C. Size-Dependent Density

Material density indicates mass per volume. Mass and volume express its normal relationship of density given as follows:

$$\rho(D_m) = \frac{m(D_m)}{V(D_m)} \quad (5)$$

Under constant temperature and pressure, bulk density is nearly constant. Nanoscale density changes with surface relaxation and lattice modification. Smaller particles have more loosely coordinated surface atoms. They may have different atomic spacing than bulk material. Lattice contraction or expansion can result from surface stress. The answer depends on metal, particle size, and shape. Therefore, density variation may vary among the six metals. Usually, its change is less than conductivity variation.

Metallic nanoparticle size-dependent characteristics are described by universal relations [10]. Pabari discussed change in nanoscale metallic particle properties [11]. Jaiswal and Pandey modelled metallic nanoparticle thermo-physics [4]. Size-sensitive treatment of basic metallic properties is supported by these studies.

A normalized density ratio can present changes from bulk density:

$$\rho_r(D_m) = \frac{\rho(D_m)}{\rho(\infty)} \qquad (6)$$

The bulk density of each metal is represented by ρ(∞). Near unity suggests little nanoscale density fluctuation. As the particle contracts, values above unity increase. Below unity, surface expansion or structural looseness may occur.

The thermal diffusivity denominator includes density. Thus, increasing density decreases diffusivity when other factors remain constant. Reduced density has the opposite mathematical impact on thermal diffusivity. Its contribution must be calculated using conductivity and heat capacity.

D. Size-Dependent Heat Capacity

Specific heat capacity indicates material temperature-raising energy. A material's thermal storage capacity is described. Well-arranged atoms with vibrational energy patterns make up bulk solids. Surface-related and confined vibrational modes are present in smaller materials.

Debye theory underpins solid heat capacity [12]. Heat capacity and permissible lattice vibrational frequencies are linked. Nanoscale vibrational frequencies vary with particle size. Therefore, bulk heat-capacity may not explain extremely tiny particles.

Patel et al. directly assessed size and specific heat [12]. Debye temperature also affected heat capacity in their study. Conductivity and specific heat variation were studied by Rawat and Goyal [5]. Khalaf and Al-Rashid found size-dependent metallic nanoparticle specific heat [13]. Size and shape effects were discussed by Singh et al. [14].

Surface and internal particle atoms bond differently. Vibrations affect thermal energy storage differently. Increased surface-to-volume ratio boosts its contribution. Thus, specific heat may alter significantly at tiny scales.

Nanoscale variation can be represented by a normalized heat-capacity ratio:

$$C_{p,r}(D_m, T) = \frac{c_p(D_m, T)}{c_p(\infty, T)} \quad (7)$$

Where, $C_p(\infty, T)$represents corresponding bulk specific heat capacity.

Nanoscale thermal energy storage improves with a ratio over 1. A ratio below unity suggests lower storage under certain situations. The response depends on size, temperature, and metal structure.

Eq. (2) denominator includes heat capacity. Increasing it lowers thermal diffusivity under normal conditions. Under similar circumstances, its reduction increases thermal diffusivity. This effect interacts with conductivity and density.

E. Surface and Boundary Effects at Reduced Sizes

Surface and boundary effects matter as material dimensions decrease. Smaller particles have more surface atoms per volume. These atoms have fewer neighbours and altered bonding. They react differently to heat in various environments.

Boundaries limit heat-carrying particle distance. In smaller metallic structures, electrons meet particle surfaces more often. Lattice vibrations disperse repeatedly at these boundaries. The scattering reduces their effective mean free movement distance.

Fuchs reported metallic film boundary conductivity variations [15]. Small crystalline structures have boundary-limited heat conduction, according to Casimir [16]. These early methods are still important for nanoscale transport research. Later, Cahill et al. thoroughly investigated nanoscale heat transport [2].

Polycrystalline materials have more separation between small grains. Grain boundaries further hinder thermal energy flow. Hori et al. linked grain structure to effective phonon travel distances [17]. Zhang et al. linked thermal conductivity to phonon movement lengths [18]. Thus, smaller grains resist heat better.

Also, surface atoms may change density and specific heat. Local spacing and effective particle volume vary with surface relaxation. Surface atom vibrational energy varies with modified bonding. This means one surface impact may affect many thermal characteristics.

Surface contribution is highest below five nanometres. At this sizes, surface atoms dominate particles. Surface influence decreases between 5 and 15 nanometres. Calculated properties then approach bulk values.

III. MATERIALS AND METHODS

A. Materials and Calculation Conditions

We chose Ag, Cu, Al, Au, Fe, and Ni. These metals vary in conductivity, density, and heat storage. Thermal comparisons benefit from their differences [4], [7]. Particle sizes were 1–15 nanometres. Regular one-nanometer calculations were done. Below five nanometres, surface effects are considerable [1], [10]. Every metal was studied with the same particle sizes.

TABLE I: CALCULATION PARAMETERS USED IN THE PRESENT STUDY

Parameter	Symbol	Condition or unit	Source
Selected metals	—	Ag, Cu, Al, Au, Fe, Ni	Present selection
Particle diameter	D_m	1–15 nm	Present selection
Size interval	—	1 nm	Present selection
Temperature	T	300 K	Present condition
Thermal conductivity	k	W m^{-1} K^{-1}	[2, 3]
Density	ρ	kg m^{-3}	Standard bulk data
Specific heat	C_p	J kg^{-1} K^{-1}	[5, 12]
Thermal diffusivity	α	$m^2 s^{-1}$	Calculated value

Bulk conductivity, density, and heat capacity were measured. The input parameters are from published research and standard sources. A 300 K temperature was maintained throughout calculations. The study considered spherical, pure, defect-free particles.

B. Size-Dependent Property Formulations

Smaller metallic particles have lower conductivity due to boundary scattering [2, 15]. This relation calculates size-dependent thermal conductivity:

$$k(D_m) = k_b \left(\frac{D_m}{D_m + \lambda_b}\right) \quad (8)$$

Where, k_b is the bulk conductivity of the selected metal, λ_b is its assumed bulk mean free path.

Particle density changed somewhat with surface contraction. This connection calculates size-dependent density:

$$\rho(D_m) = \frac{\rho_b}{\left(1 - \frac{0.01}{D_m}\right)^3} \quad (9)$$

Where, ρ_b is the corresponding bulk density value.

The assumed surface contraction is shown by the coefficient 0.01nm. Smaller particles could hold more heat when the surface vibrated [5, 12]. The following equation was used to figure out the size-dependent heat capacity:

$$C_p(D_m) = C_{p,b}\left(1 + \frac{0.15}{D_m}\right) \quad (10)$$

Where, $C_{p,b}$ is corresponding bulk specific heat capacity.

The surface input is shown by the coefficient 0.15nm. During the six-metal comparison, neither of the coefficients changed.

C. Thermal Diffusivity and Comparative Analysis

Thermal diffusivity was calculated from the three size-dependent properties:

$$\alpha(D_m) = \frac{k(D_m)}{\rho(D_m)\, C_p(D_m)} \quad (11)$$

The math was done again and again for each metal and particle diameter. For the final measurements, bulk numbers were used as a standard. To find the percentage difference from the bulk diffusivity, we did the following:

$$\%\,\Delta\alpha = \frac{\alpha(D_m) - \alpha_b}{\alpha_b} \times 100 \quad (12)$$

Diffusivity was less than the corresponding bulk value when the value was negative. As values got closer to zero, they showed that the bulk behaviour was moving back to normal. The estimated temperature trends were shown in tables. Along the horizontal line of each graph, the particle width was shown. Along the matching vertical line, thermal characteristics showed up. Particle sizes less than five nanometres were given extra attention. Studies that were reported backed up the interpretation of the calculated trends [2, 4].

IV. RESULTS

The values shown were found using the chosen theoretical model. They shouldn't be thought of as direct measurements from an experiment.

A. Size-Dependent Thermal Properties of Silver

TABLE II: SIZE-DEPENDENT THERMAL PROPERTIES OF SILVER AT 300 K

Size (nm)	Conductivity (W $m^{-1}K^{-1}$)	Density (kg m^{-3})	Heat capacity (J $kg^{-1}K^{-1}$)	Diffusivity ($\times 10^{-6}$ m^2s^{-1})
1	8.09	10,811.10	270.25	2.770
3	23.40	10,595.60	246.75	8.950
5	37.63	10,553.19	242.05	14.732
10	69.19	10,521.53	238.52	27.571
15	96.04	10,511.01	237.35	38.498
Bulk Ag	429.00	10,490.00	235.00	174.026

Across the chosen particle sizes, silver showed clear changes in temperature. As the particle diameter went from 1 to 15 nm, conductivity kept going up. Density and heat capacity got closer and closer to their mass values. These changes together made heat diffusivity go up as particle size went up.

It became more conductive with silver, going from 8.09 to 96.04 W$m^{-1}K^{-1}$. Its weight went down from 10,811.10 to 10,511.01 kgm^{-3}. The heat capacity went down from 270.25 J/kg to 237.35 J/kg K^{-1}. It caused the diffusivity to rise from 2.770 to 38.498 $\times 10^{-6}$m^2 s^{-1}. Still, the 15 nm value was less than the bulk silver diffusivity.

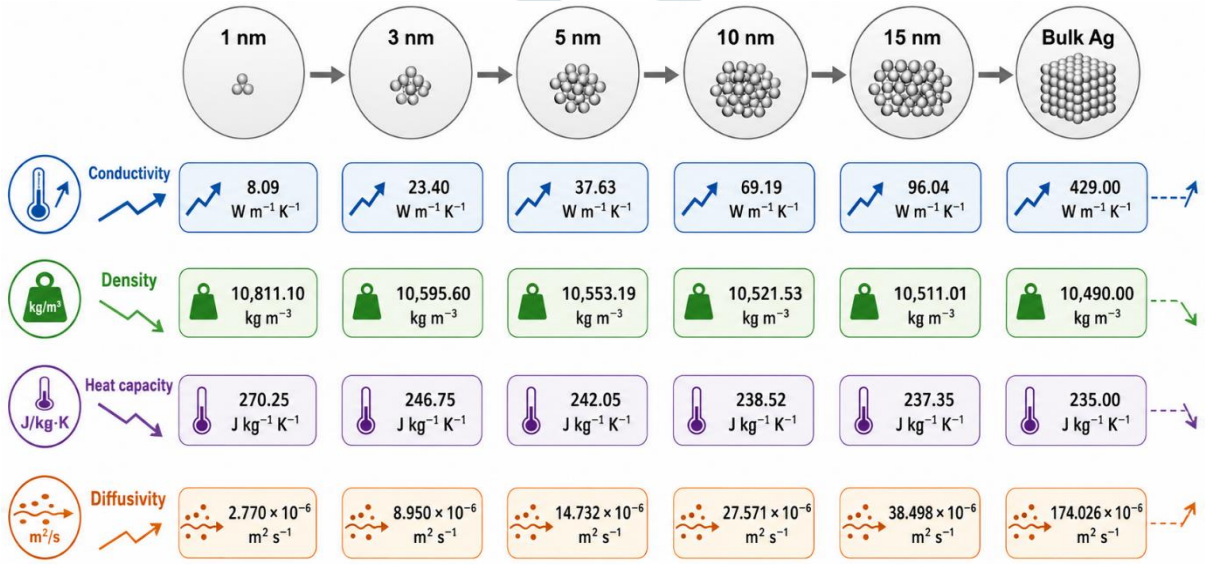

Fig. 1. Size-dependent thermal diffusivity of silver at 300 K

The curve should show diffusivity against particle diameter from 1–15 nm. A horizontal dotted line should represent the bulk silver value.

B. Comparative Results of Selected Metals

All six metals showed that as particle width went up, diffusivity went up as well. At fifteen nanometers, their values stayed below the mass amounts that were expected. In the range that was chosen, aluminium had the largest predicted diffusivity. The least amount of heat was spread by iron and nickel.

The diffusivity ranged from 1.763 to 4.857 at 1 nm. Prices ranged from 13.626 to 46.788 nm at 15 nm. Aluminium came in first because it spread heat more easily because it has a lower mass. The nanoscale diffusivity values for silver, gold, and copper were all about the same. Throughout the chosen particle range, iron and nickel stayed lower.

TABLE III: MODEL-GENERATED THERMAL DIFFUSIVITY OF SELECTED METALS

Metal	Thermal Diffusivity (in 10^{-6}m² s^{-1})				
	1 nm	5 nm	10 nm	15 nm	Bulk value
Ag	2.770	14.732	27.571	38.498	174.026
Cu	2.452	12.748	23.303	31.907	116.245
Al	4.857	22.485	36.970	46.788	97.857
Au	2.752	14.273	26.029	35.570	127.193
Fe	2.132	8.441	12.410	14.655	22.741
Ni	1.763	7.393	11.288	13.626	22.983

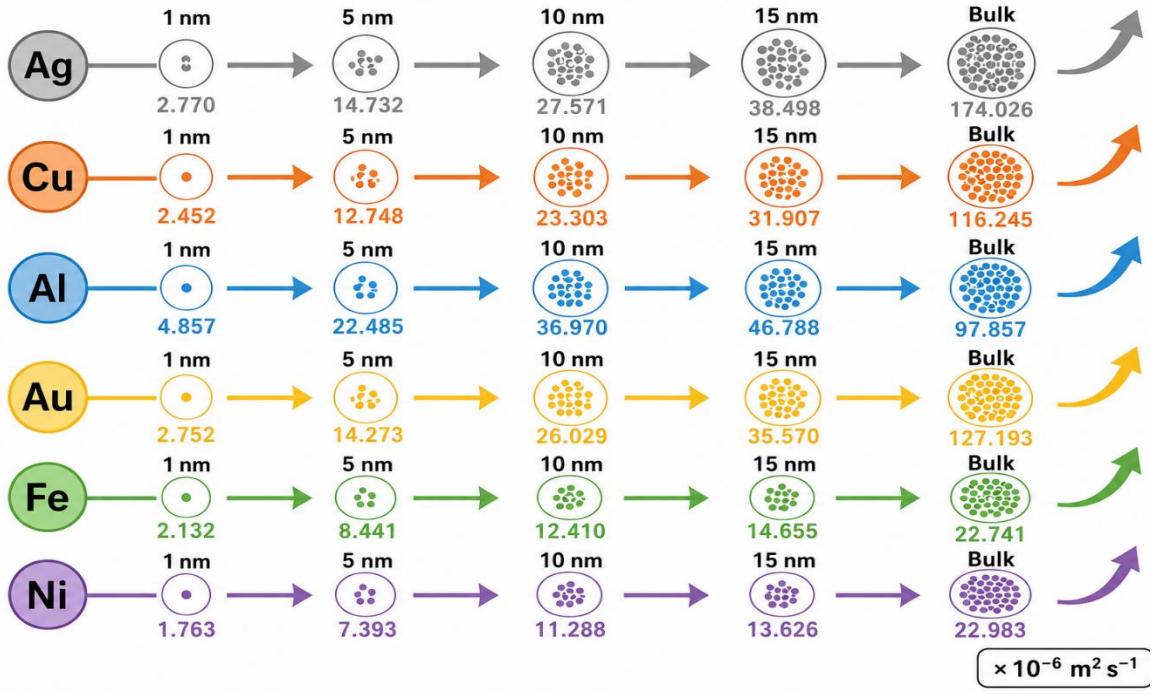

Fig. 2. Model-generated thermal diffusivity of different particle sizes

V. DISCUSSION

A. Influence of Thermal Properties

The factor that had the most impact on the estimated thermal diffusivity was thermal conductivity. The numerator of the diffusivity equation went down directly because it went down. Boundary scattering limited the movement of electrons and lattices inside smaller particles [2]. Kumar and Singh [3] also found effects on grain size that were similar to these.

Density and heat capacity made smaller but important changes. The quantity of silver went up a little because the area is thought to have shrunk. Its heat capacity went up because of more vibrations related to the surface. Both changes made it even less likely for very small silver particles to move.

The conductivity of silver stayed 98.11% lower than the conductivity of copper at 1 nm. The density stayed 3.061% higher than its bulk value. It kept its 15.00% higher heat capacity than the bulk number. All of these changes made the silver less diffusive by about 98.41%.

At fifteen nanometres, the density effect shrunk a lot. The heat capacity got closer to its bulk value as well. So, conductivity stayed the main trait that controlled diffusivity in the equations. This combined treatment matched the models of metallic nanoparticles that had been published [1, 4].

B. Particle-Size and Material Behaviour

The particle diameter was less than five nanometres, and the most significant thermal changes were observed. Within these smaller particles, a higher proportion of surface atoms were present. The effective movement of heat-carriers across particles was shortened by frequent boundary interactions. This behaviour is also supported by classical boundary theories [15-16].

At a wavelength exceeding five nanometres, the influence of the surface progressively diminished. Between 5 and 15 nanometres, the diffusivity of each metal increased. Nevertheless, no metal was chosen to achieve its bulk value at 15 nm.

The modelled diffusivity of aluminium was the highest across all selected sizes. Its relatively high heat capacity was effectively mitigated by its low density. At fifteen nanometres, silver exhibited the second-highest diffusivity. Gold and copper supplied intermediate nanoscale heat-spreading behaviour. Nickel and iron exhibited the lowest values in this model.

C. Literature Comparison and Practical Importance

The conductivity trend that was calculated was consistent with the results of the nanoscale transport investigations that were reported. Strong boundary effects within smaller materials were described by Cahill et al. [2]. Fuchs elucidated the surface-limited electron migration within thin metallic structures [15]. Casimir also described boundary-controlled heat transport within minuscule crystals [16].

The heat-capacity trend corresponded with previously established theoretical discoveries regarding nanoparticles. Rawat and Goyal jointly reported variations in specific heat and conductivity [5]. Patel et al. established a correlation between particle-size variation and heat capacity [12]. Similar metallic heat-capacity behaviour was reported by Khalaf and Al-Rashid [13].

The findings may provide evidence to substantiate preliminary decisions regarding the selection of nanoscale materials. Aluminium may be appropriate for lightweight components that necessitate improved heat dissipation. Silver may be beneficial for applications that require high thermal performance and stability. Nickel and iron may be suitable for structural and magnetic applications.

The most significant reduction in thermal diffusivity was observed in particles that were less than five nanometres in size. The heat diffusion within the investigated range was enhanced by larger particulates. Experimental validation is still required prior to direct engineering application.

VI. LIMITATIONS OF THE STUDY

The study employed theoretical models that were not directly experimentally validated. Consequently, its outcomes are contingent upon the input parameters and selected equations. Only particles that were spherical in shape and ranging from one to fifteen nanometres in size were taken into account. Additionally, a single standard temperature of 300 K was employed in the calculations.

Defects, coatings, fissures, and irregular geometries may be present in the actual particles. Aluminium, iron, copper, and nickel may be particularly susceptible to oxidation. This investigation did not address particle contact, agglomeration, or surrounding-medium effects. The conductivity and measured thermal diffusivity values may be altered by these factors.

VII. CONCLUSION

The thermal diffusivity of six metallic nanoparticles, each measuring between 1 and 15 nanometre, was compared in the study. The size-dependent effect was most pronounced when conductivity was measured. The silver diffusivity increased from 2.770×10^{-6} to $38.498 \times 10^{-6} m^2\ s^{-1}$. The low density of aluminum resulted in the greatest modelled nanoscale diffusivity. Below 5 nm, the most significant deviations were observed. Experimental validation is still required prior to practical application.

VIII. FUTURE SCOPE

The results may be verified through laser-flash measurements in future studies. Diverse temperatures, defects, surface coatings, and particle morphologies may also be investigated. Electronic and lattice contributions may be distinguished by sophisticated models. The method can be subsequently expanded to encompass alloys and metallic composites [19, 20].

IX. NOVELTY OF THE WORK

Six metals are compared in this study under identical calculation conditions. Through thermal diffusivity, it establishes a connection between density, conductivity, and heat capacity. Particle sizes ranging from 1 to 15 nm are the subject of comprehensive silver calculations. Under the adopted assumptions, the common framework also identifies aluminium as the most powerful nanoscale heat-spreading material.

Acknowledgment

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability

All model-generated data are included within this paper.

X. REFERENCES

[1] L. Qiu *et al.*, "A review of recent advances in thermophysical properties at the nanoscale: From solid state to colloids," *Physics Reports*, vol. 843, pp. 1–81, 2020, doi: 10.1016/j.physrep.2019.12.001.

[2] D. G. Cahill *et al.*, "Nanoscale thermal transport," *Journal of Applied Physics*, vol. 93, no. 2, pp. 793–818, 2003, doi: 10.1063/1.1524305.

[3] A. Kumar and M. Singh, "Impact of grain size on thermal conductivity of nanomaterials," *Nanotechnology Perceptions*, vol. 20, no. 4, pp. 877–893, 2024, doi: 10.62441/nano-ntp.v20i4.5408.

[4] R. L. Jaiswal and B. K. Pandey, "Modelling for the study of thermophysical properties of metallic nanoparticles," *SN Applied Sciences*, vol. 3, no. 4, Art. no. 466, 2021, doi: 10.1007/s42452-021-04478-8.

[5] K. Rawat and M. Goyal, "Theoretical study of specific heat and thermal conductivity variation in nanomaterials," *High Temperatures–High Pressures*, vol. 49, pp. 279–298, 2020.

[6] A. Kumar and M. Singh, "Study of size dependent thermal conductivity of gold FCC nanomaterial," *American International Journal of Research in Science, Technology, Engineering & Mathematics*, vol. 26, no. 1, pp. 134–136, 2019.

[7] M. Singh, B. Taele, S. Lara, S. Singhal, and K. Devlal, "Modelling thermodynamic properties of Ni, Sn, Al and Cu nanosolids," *High Temperatures–High Pressures*, vol. 51, pp. 403–418, 2022, doi: 10.32908/hthp.v51.1263.

[8] H. Ju, S. Zhang, Z. Li, X. Shui, and P. Kuo, "Size-dependent thermal diffusivity of multilayered thin films deposited on substrates characterized by transient grating technique," *Applied Physics Letters*, vol. 94, no. 3, Art. no. 031902, 2009, doi: 10.1063/1.3067903.

[9] A. Karamati, M. Han, X. Duan, Y. Xie, and X. Wang, "Thermal diffusivity characterization of semiconductive 1D micro/nanoscale structures," *International Journal of Heat and Mass Transfer*, vol. 233, Art. no. 126012, 2024, doi:10.1016/j.ijheatmasstransfer.2024.126012.

[10] S. Xiong, W. Qi, Y. Cheng, B. Huang, M. Wang, and Y. Li, "Universal relation for size dependent thermodynamic properties of metallic nanoparticles," *Physical Chemistry Chemical Physics*, vol. 13, no. 22, pp. 10652–10660, 2011, doi: 10.1039/c0cp90161j.

[11] C. Pabari, "Size dependent properties of metallic nanoparticles," *Materials Today: Proceedings*, vol. 55, no. 1, pp. 98–101, 2022, doi: 10.1016/j.matpr.2021.12.375.

[12] G. R. Patel, N. A. Thakar, and T. C. Pandya, "Effect of size on specific heat and Debye temperature of nanomaterials," *AIP Conference Proceedings*, vol. 1728, no. 1, Art. no. 020115, 2016, doi: 10.1063/1.4946189.

[13] S. F. Khalaf and S. N. T. Al-Rashid, "Size-dependent melting entropy and specific heat of metallic nanoparticles: A cohesive energy-based theoretical approach," *Journal of Nanoparticle Research*, vol. 27, Art. no. 78, 2025, doi: 10.1007/s11051-025-05876-2.

[14] M. Singh, S. O. Lara, and S. Tlali, "Effects of size and shape on the specific heat, melting entropy and enthalpy of nanomaterials," *Journal of Taibah University for Science*, vol. 11, no. 6, pp. 922–929, 2017, doi: 10.1016/j.jtusci.2016.09.011.

[15] K. Fuchs, "The conductivity of thin metallic films according to the electron theory of metals," *Mathematical Proceedings of the Cambridge Philosophical Society*, vol. 34, no. 1, pp. 100–108, 1938, doi: 10.1017/S0305004100019952.

[16] H. B. G. Casimir, "Note on the conduction of heat in crystals," *Physica*, vol. 5, no. 6, pp. 495–500, 1938, doi: 10.1016/S0031-8914(38)80162-2.

[17] T. Hori, J. Shiomi, and C. Dames, "Effective phonon mean free path in polycrystalline nanostructures," *Applied Physics Letters*, vol. 106, no. 17, Art. no. 171901, 2015, doi: 10.1063/1.4918703.

[18] H. Zhang, C. Hua, D. Ding, and A. J. Minnich, "Length dependent thermal conductivity measurements yield phonon mean free path spectra in nanostructures," *Scientific Reports*, vol. 5, Art. no. 9121, 2015, doi: 10.1038/srep09121.

[19] C. Lu and X. Zhang, "Effect of size-dependent thermal conductivity on heat transfer and fluid flow in TiC-reinforced nanocomposites during moving annular laser melting," *International Journal of Thermal Sciences*, vol. 220, Part A, Art. no. 110312, Feb. 2026, doi: 10.1016/j.ijthermalsci.2025.110312.

[20] G. T. Sherka, H. D. Berry, and Q. Zhang, "Size and shape dependent cohesive energy and melting temperature in semiconducting nanomaterials," *Discover Nano*, vol. 21, Art. no. 67, 2026, doi: 10.1186/s11671-026-04485-x.