EUROPEAN JOURNAL OF PURE AND APPLIED MATHEMATICS
2025, Vol. 18, Issue 4, Article Number 7166
ISSN 1307-5543 – ejpam.com
Published by New York Business Global

A Comprehensive Review on Structure of Heat and Fluid Flow in Liquid Metals at Low Grashof Number

Hossam A. Nabwey[1,*], Hajra Nadeem[2], Muhammad Ashraf[2], A. M. Rashad[3], Ali J. Chamkha[4]

[1] *Department of Mathematics, College of Science and Humanities in Al-Kharj, Prince Sattam bin Abdulaziz University, Al-Kharj 11942, Saudi Arabia*
[2] *Department of Mathematics, University of Sargodha, Sargodha 40100, Pakistan*
[3] *Department of Mathematics, Faculty of Science, Aswan University, Aswan, Egypt*
[4] *Faculty of Engineering, Kuwait College of Science and Technology, Doha District, 35004, Kuwait*

Abstract. The current study presents the comprehensive review of heat transfer in liquid metals at low Grashof numbers. Heat transfer in liquid metals is extremely efficient because their substantial thermal conductivity enables heat to travel swiftly, even when natural convection is minimal. At low Grashof numbers, buoyant forces are relatively weak in comparison to viscous forces, hence heat transfer in liquid metals is mainly governed by conduction instead of convection, resulting in restricted fluid motion and decreased thermal transport. The most commonly utilized liquid metals in engineering are alkali metals. Sodium, for example, is primarily employed as a coolant in fast reactors and a working fluid in high-temperature heat pipes. Potassium is an excellent working material for space power plants. Eutectic Na-K and Pb-Bi alloys, as well as Hg, Li, and Ga, may be employed in certain instances. A detailed literature review is needed to compare previous studies under various conditions and highlight the influence of controlling factors such as the Grashof number. This review also discusses the practical importance of comprehending low Grashof number heat transfer for innovative cooling technologies in nuclear, space, and solar thermal applications.

2020 Mathematics Subject Classifications: 80A19

Key Words and Phrases: Heat transfer, liquid metals, low Grashof number, thermal conductivity, restricted fluid motion

1. Introduction

Liquid metals have been found to be highly thermal conductive and have a unique flow behaviour that makes them good candidates to be used in future heat transfer applications in areas like nuclear reactors, electronics, cooling and solar energy systems.

*Corresponding author.
DOI: https://doi.org/10.29020/nybg.ejpam.v18i4.7166

Email addresses: eng_hossam21@yahoo.com (H. A. Nabwey)

When the Grashof numbers are low, such that the influence of buoyancy is relatively low, the heat and fluid flow in liquid metals are dominated not by the strong natural convectional currents but by conduction and forced convection. The importance of this regime is that it demonstrates the underlying transport processes that govern thermal performance of small systems and in small geometries. Low Grashof number experiments also lay the groundwork for forecasting flow and heat transfer behaviour in mixed and turbulent convection regimes, hence facilitating the development of dependable, high-performance cooling solutions. To explain the characteristic of the liquid metals in low Grashof number more thoroughly, helps to establish the effective cooling system when the heat transfer is predicted and remains stable. Furthermore, many sophisticated thermal systems, such as micro-reactors, electronic cooling channels, and small heat exchangers, operate in conditions with negligible buoyancy effects. Investigating conduction-dominated heat transport in these situations aids in temperature homogeneity, preventing isolated hotspots, and ensuring operational reliability. The purpose of this review is to go over in depth the structure of heat and fluid movement in liquid metals under these conditions, some of the most important discoveries made by previous scientists, and the issues and directions of future research.

Ahmad et al. [1] proposed a numerical analysis of unsteady flow as well as heat transfer in a viscous-type nanofluid, focusing on the effect of microorganisms on a moving surface coming from a moving slot. Akhmedagaey et al. [2] demonstrated that even with strong magnetic fields causing high Grashof and Hartmann numbers, roll instabilities and significant temperature variations can also occur in flows of liquid metals, which is significant in the use of fusion reactors. Ali et al. [3] emphasized the necessity of regulating fluid flow with the Riga plate in the presence of suction and explores the behaviour of a specific nanofluid under these conditions. Ali et al. [4] explored the entropy formation and the influence of magnetic field on the peristaltic motion of copper-water tiny fluid in an asymmetrical configuration saturated with porous material. Ali et al. [5] investigated the effect of Cu-Al2O3 magnetohydrodynamics hybrid nanofluid on heat transport and flow in a porous channel with heat flow and viscous dissipation effects. Ali et al. [6] examines the impact of thermal radiation and Joule heating on the magnetohydrodynamic flow of a hybrid nanofluid on a stretched cylinder. Ali et al. [7] emphasized the necessity of regulating fluid flow with the Riga plate in the presence of suction and explores the behaviour of a specific nanofluid under these conditions. Ali et al. focussed on the impact of stretching, shrinking, and porous barriers on flow and thermal properties in [8] and analyzed heat transfer in MHD Jeffrey nanofluid movement across a nonlinear, variable thick elongating surface in [9]. Ali et al. [10] concluded that the Soret and Dufour number enhances the temperature of the fluid while decreasing the concentration. An et al. [11] provided a detailed overview of liquid metal-based mini/micro-channel heat transfer technology. Ashraf [12] investigated the thermophysical properties of heat and fluid movement, emphasizing their significance in determining environmental outcomes and implications.

A thermophoretic motion, as well as temperature-dependent thermal conductivity on the natural convection flow in the surface of a sphere at multiple circumferential points was introduced by Ashraf et al. [13]. The periodic behaviour of convective heat transfer properties of the fluid flow were discussed by Ashraf et al. [14] under scrutiny of the cone which is electrically conducting embedded in the porous medium with the presence of viscous dissipation in energy equation. Azad et al. [15] revealed that the liquify volume at the start of spontaneous heat transport falls nonlinearly as the Gr rises. Azer and Chao [16] created a novel method for studying how heat transfers in liquid metals moving through pipes, and they discovered that their estimations for temperature, heat transfer, and flow behaviour match actual observations, particularly for extremely low Prandtl number settings. Benderradji et al. [17] discussed numerically combined natural and forced convection in a cubic cavity. They demonstrated that the stream changes from natural to forced convection for different Reynolds and Grashof numbers and compared with the literature. Benderradii et al. [18] offered a numerical examination of stationary laminar mixed convection in a vented four-sided chamber. Horizontal magnetic fields were also studied by Chen et al. [19] in relation to the thermal convection of liquid metals, which demonstrated substantial impacts on the morphology of the flow and the worldwide thermal transport in the liquid. Dawood et al. [20] presented a detailed review on improving the thermal efficiency of heat swapping equipment and transporting energy at a cheap cost. Mechanisms of convection in liquid metal fluids, along with techniques used to drive them, common applications, and enhancement methods, were introduced in [21]. In addition, the scientific problems and future perspectives of liquid metal convection were also addressed. Dudek et al. [22] gave the research on the experimental evaluation and numerical computation of both the stable and transient free convective resistance around spherical shapes with low Grashof values. Molten metals have been considered as effective heat transport fluids for thermal solar power applications due to their excellent heat capacity and thermal conductivity in [23].

Fritsch et al. [24] conducted conceptual research on central receiver systems that used fluid metals as efficient heat transport fluids especially in Concentrated Solar Power plants, demonstrating their potential for better thermal performance. An experimental hypersonic air-intake leading edges liquid metal heat-pipe solution concept, numerical analysis and verification have been defined by Fusaro et al. [25]. Ganeshkumar et al. [26] investigated the exergy efficiency and entropy production of shot-blasted heat exchangers using two different nanofluids: solar glycol with activated carbon as well as solar glycol with multi-walled carbon nanotubes. Free convection in an annulated region situated between two straight eccentric cylinders was investigated by Ghernoug et al. [27], considering air as a fluid with multiple data of Grashof number. Giometto et al. [28] examined stably stratified turbulent flows over inclined smooth surfaces at high Grashof numbers using direct numerical simulation and found that slope angle significantly affects mean flow, energy distribution, and turbulence in anabatic and katabatic regimes. Guo et al. [29] presented the straight numerical calculation of combined convection unsteady heat transport in a straight channel for fluid lead. Heinzel et al. [30] presented the benefits of fluid metals for applications as heat transport fluids in terms of high thermal conductivity and low viscosity. They also pointed out that advancements in research in this field have lessened some of the technical and safety barriers seen in earlier research, which would create a foundation for more applications. The linear stability in a downward moving liquid metal vertical duct in the existence of intense wall heating and a transverse magnetic field was studied numerically by Hu [31]. Jaeger et al. [32] discussed liquid metal thermal transfer under free to forced convection, and demonstrated the Peclet number dependency, and the need for better models and experiments. Kamiyo et al. [33] provided a detailed review on free convection in triangular containers.

Natural heat transfer in a liquid metal warmed regionally at its top area and subjected to an upright magnetic field was examined by Karcher et al. [34] experimentally and numerically. Free convection in a fluid metal warmed nearby at its top surface and subjected to a upright magnetic field was studied experimentally and mathematically by Karcher et al. [35]. Ke et al. [36] focused on a temporally developing turbulent buoyancy driven surface layer close to an isothermally warmed upright wall with Pr = 0.71 and high Grashof number. Khan et al. [37] presented research to discuss the physical phenomenon of free convection nanofluids heat transfer down a sphere and fluid eruption through the boundary layer into a plume region above the surface of the sphere. The computational investigation of smooth mixed heat transfer in a lid-driven hollow with altered heated bottom wall was carried out by Khanafer [38] for different Grashof and Richardson numbers. The flow of isothermal rounded particles in a 2D upright channel, limited by warm and cold adiabatic walls and affected by thermal convection at low Grashof number, was studied by Kim et al. [39]. Direct numerical simulation was used by Kis and Herwig [40], to study the turbulent natural convection of air between two upright infinite surfaces at fixed temperatures throughout a range of Grashof numbers. Kroeger and Ostrach [41] found that during the continuous metal processing, natural convection can be considerable at Grashof numbers of $10^5 - 10^6$, but has no impact on the solid-liquid edge location. Laminar natural convection created by a line thermal source was investigated by Linan and Kurdyumov, revealing that heat transfer from wires [42] is still conquered by conduction at low Grashof numbers. Li with others in [43] concluded that the pressure loss in magnetohydrodynamics peripheral flow is comparable to that in single-state magnetohydrodynamics pipe flow under identical fluid metal flow conditions.

The results in [44] showed that for a high value of Gr, the thermal rate of the nanofluid enhances dramatically with an upsurge in nanoparticle mass ratio, and that for small Gr values, the heat transport process is dominated by warm exchange, whereas for large Gr values, it is dominated by free convection. Liu and Liu [45] discussed convective cooling of liquid metals at high power density electronics, and low-melting alloys like In-Ga-Sn alloys, and pointed out thermophysical property equations, model of heat transfer and flow resistance. Liu et al. [46] quantitatively studied the thermal transfer presentation of array jet impingement using liquid metals as coolant, with an emphasis on parametric influences to create an ideal design. Lorenzin and Abanades [47] stated that fluid metals are potential heat transport fluids for next generation Concentrated Solar Power systems, but their suitability with materials, security problems, and thermophysical characteristics must all be verified at large temperatures. Lyon and Poppendiek [48] offered one of the first coordinated studies of liquid-metal heat transport, stressing their high thermal conductivity and unique behavior when compared to conventional fluids. Lyu et al. [49] analysed the convective magnetohydrodynamics stream in a simple rectangular cavity model which includes a coaxial spherical cooling pipe which is preserved at fixed temperature whilst the fluid undergoes a uniform volumetric heating. The effects of spin on the following vortex and thermal transport from a big diameter straight spinning pipe in still air were experimentally investigated by Ma et al. [50]. A detailed analysis of chip cooling with low-melting-point liquid metals and alloys has been published in [51], with a focus on thermal characteristics and prospective applications in advanced electronic cooling. Mahony [52] proposed that the heat transport from a body submerged in a liquid be estimated only by the thermal transport equation when the Grashof number, Gr, connected to the situation is low. The application of standards for the forced-to-combined convection transition in moderate to strong Pr (Prandtl number) fluids was examined by Marocco with others [53] and expanded to include low Pr fluids such as heavy liquid metals.

McBain and Stephens [54] discovered that in a fluid-filled spherical cavity with small Grashof numbers, convective effects are minimal and heat transmission occurs mostly by conduction. Mebarek and Bessaïh [55] numerically examined transient magnetohydrodynamics free convection between upright coaxial pipes and reported that flow steadiness and heat transort depend on the aspect ratio, Hartmann numbers, and the orientation of the magnetic field. Medrado [56, 57] gave the experimental results that indicate a sustained stable recirculation region nearby the air-water boundary for Gr values over or equal to 50. A calculation for calculating the coefficient of thermal transport in a pipe with a oscillatory flow that takes natural convection into account was presented by Mikhailov et al. [58]. Experimental research on NaK and mercury flowing via rod bundles were utilized by Mikityuk [59] to enhance the heat transfer correlation, resulting in better estimates for liquid-metal-cooled reactor and heat exchanger designs. Mohamad and Viskanta [60] examined the turbulent free convection in a chamber occupied with fluids having a low Prandtl value. The effects of Reynolds as well as Grashof numbers on the steady natural circulation flow were experimentally studied with the FASSIP-02 important test loop by Moniaga et al. [61]. Moundjia and Samah [62] investigated a mathematical analysis of buoyancy driven in permeable media described by the Darcy-Brinkman-Forchheimer comparison at small Grashof numbers, in a permeable square inclusion. The impact of nanoparticle-induced Brownian and thermophoresis diffusion, as well as boundary deformation, on several physical variables were investigated in [63].

Direct computational simulations were used in [64] to study mixed convection in liquid metal flow in a straight pipe. Nabwey et al. [65] gave a comprehensive review that covers the essential ideas of entropy production reduction and their significance in the growth of renewable energy systems. Nabwey et al. [66] summarized the most important published works on improving convective thermal transfer in the occurrence of humid air, as well as its physical implications. The impact of dimensionless operating parameters on the dimensionless thermal transfer coefficient in a liquid metal flow in a circular tube was investigated by Ogneruboy and Listratov [67]. Oyinloye et al. [68] described the findings from an experimental examination of CO_2 desublimation on a cylindrical, highly conductive surface. Pacio et al. [69] undertook a careful assessment of the experimental data and heat transfer correlations published in the literature for fully developed, forced-convective liquid metals in pipes. Pacio and Wetzel [70] presented liquid metals as enhanced heat transport fluids, identifying sodium (Na), tin (Sn), and lead-bismuth (PbBi), as promising possibilities and examining their different benefits and limits. An inter-wrapper flow and heat transfer study was conducted on liquid metal-cooled fast reactors and presented information on thermal behaviour and safety in [71]. Rahimi et al. [72] discussed natural convection in enclosures with different geometries, boundary conditions and fluids, with emphasis on the effect on heat transfer and applications in industrial processes. Rong et al. [73] examined the flow structure of persuaded airflow with respect to the liquid flow state, the influence of changes in Grashof number and flow rate, and the primary variable spatial series of the persuaded airflow.

The application of liquid gallium in metal inserts was proposed by Salyan et al. [74] as a different method for improving thermal transmission in solar thermal energy storage systems. Samanta and Chattopadhyay [75] extended the use of the lattice Boltzmann process to tackle solid-to-liquid phase change issues using low Prandtl number materials. Sarowar [76] examined the thermal presentation of a small network heat descend using five distinct substrate materials (aluminum nitride, titanium diboride, beryllium oxide, zirconium diboride, and hafnium diboride) and four distinct gallium alloys. Shah et al. [77] systematically reviewed the experimental studies on the influence of Grashof number and free to forced convection parameter and concluded that an rise in buoyancy causes an upsurge in velocity and a reduction in temperature with varying impacts on the heat with mass transfer characteristics. The production of heat convection flow in the molten metal battery, a technology described as a viable explanation to the problem of temporary energy storage, was investigated by Shen and Zikanov [78] using a numerical model. Shevaladze et al. [79] studied Grashof number computation in large-scale passive cooling structures, with a focus on temperature-induced fluctuations. Free convection between spheres that are concentric was investigated by Singh and Chen [80] for Grashof numbers that varied from $1,000$ to $20,000$, revealing similar flow and heat transmission trends with previous results. Stewart and Weinberg gave the experimental [81] and theoretical [82] analysis on fluid flows in liquid metals at low Grashof number. Their results showed that flow rates rise with growing temperature differential among the liquid cell, regular temperature, and liquid layer thickness. Suri et al. [83] examined numerically smooth heat transfer in power-law fluids spanning the region of vanishingly tiny Grashof number ($10^{-4} \leq \mathrm{Gr} \leq 10$) for a solitary sphere and twin spheres with changing center-to-center distances.

Theoretical models, design issues and applications of high-temperature liquid-metal heat pipes were summarized in a review by Tian et al. [84], in which performance limits and pragmatic guidelines were outlined. Ullah et al. [85] investigated the effects of decreased gravity and magnetohydrodynamics on alternating mixed-convective electrically conducting fluid flow over a heated, non-conducting straight circular cylinder. Wang [86] summarized the heat exchanger tube rupture accidents in reactors, which would be of importance for the safety evaluation. The study found that although some phenomena are well researched, others need more research and better tools in the field. Wang et al. [87] examined liquid metals due to their special thermal characteristics, their uses as thermal interface materials, phase change materials and heat transfer fluids as well as the challenges facing their uses and directions of future uses. [88] concluded that alloy thermal interface materials (TIMs), with higher conduction, flexibility, and lower melting points than conventional Thermal Interface Materials, show promise in electronics, soft devices, and bio-heat transfer, though barriers to widespread implementation remain. Wang et al. [89] numerically examined the liquid metal free convection on a vertical plate and proved that Gr and magnetic field strength have a great effect on the heat transport and flow features. Wolff et al. [90] did a collective experimental and mathematical study on free convection of liquid metals in upright hollows. They concluded that free convection in liquid metals differs significantly from that in strong Pr fluids. Xie et al. [91] investigated the hydrodynamic reply of liquids, focusing on the creation instruments of splashing and hollow shape, as well as their connections with motion of particles, while taking contact line motion into account. Yao et al. [92] summarized the features, heat transfer models, and application research developments of liquid metal phase change materials. Zhang et al. [93] solved low thermal volume of liquid metals by introducing manifold structure where they demonstrated that a liquid metal manifold temperature sink has high cooling capacity and efficiency. Also, Zhang [94] concise the single-phase convective thermal transport of liquid metal, that is helpful for scientists as well as engineers involved in liquid metal convection thermal transfer.

Zurner et al. [95] experimentally investigated turbulent Rayleigh-Benard heat transport in liquid metal (GaInSn) at small Prandtl number, and found complicated large-scale circulation structure, Reynolds number dependence and heat transfer scaling in good agreement with simulations. Zwirner et al. [96] considered the effect of cell elevation on thermal transfer and important rotation in liquid metallic convection. The novelty of the review is that it focuses only on heat and fluid movement in liquid metals with low Grashof values. This regime is sometimes overlooked when compared to high Gr investigations, although it is critical for understanding conduction-dominated heat transport. The paper also applies these findings to contemporary micro-scale and high-performance cooling systems.

2. Thermophysical Properties of Liquid Metals

Table 1 evaluates the viscosity η of several liquid metals, as reported in the original source. While the provided statistics are consistent with the relevant literature, inconsistencies between the calculated and experimental values suggest that Kim and Chair's [97] correlation given in equation (1) is an estimate. These distinctions underscore the difficulties in adequately simulating the thermophysical characteristics of liquid metals, which are extremely sensitive to temperature and impurities.

$$\eta = \frac{2(MT)^{1/2}}{V}\left[C_V\left(1-\frac{1}{\gamma}\right)\right]^{1/2}\lambda, \tag{1}$$

and compared them with the experimental values. Here, M is the molar mass, T is the temperature in kelvin, V is the specific volume, C_V is the specific heat at constant volume, and γ is the ratio of specific heats. The calculated and experimental numbers are given below:

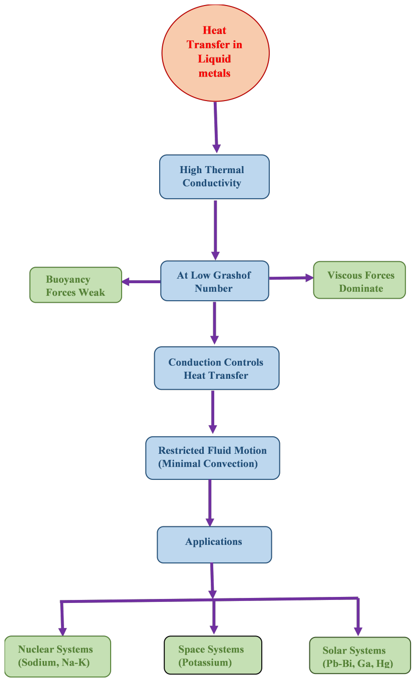

Figure 1: Flowchart of the role of heat transfer in liquid metals at low Grashof number.

3. Dimensionless numbers and flow characteristics

3.1. Grashof number

One important dimensionless ratio that determines the behaviour of fluid flow and heat in liquid metals is the Grashof number (Gr). It shows how much more significant are buoyant forces compared to viscous forces in determining whether it is conduction, laminar convection or turbulent convection which dominates the heat exchange process. Heat transport at very low Grashof values is largely conduction based whereas at intermediate values, natural convection occurs. The higher the Grashof number the more important is convection and at numbers large enough completely developed turbulent convection is seen. Table 1 identifies these different flow regions and demonstrates the change in behaviour of heat transfer in liquid metals with change in Grashof value.

3.2. Prandtl number

The Prandtl number $\mathrm{Pr} = \frac{\nu}{\alpha}$ is the ratio of diffusivity to momentum. The value of Pr in liquid metals is very low, with a range of $10^3 - 10^2$. This implies that heat diffuses slower compared to momentum. This causes the velocity boundary layer to be very thin compared with the thermal boundary layer and the flow patterns and transition behaviours are very different as found in high-pressure fluids, such as air or water.

Table 1: Values of different liquid metals at different temperatures

Liquid Metal	**Temperature T (K)**	$\eta_{\textbf{calculated}}$	$\eta_{\textbf{observed}}$
Na	376.6	6628	6860
	440.6	4205	5040
	523.0	3308	3810
	623.0	2844	2690
K	342.9	5146	5150
	440.4	3265	3310
	523.0	2760	2680
	623.0	2473	1910
Rb	311.0	6789	6734
	320.9	6180	6258
	371.7	4643	4844
	413.5	4016	4133
Pb	729.0	21378	20590
	842.0	17964	17000
	976.0	15995	13490
	1117.0	14831	11850
Cs	316.4	6258	6299
	371.6	4555	4753
	413.5	3972	4065
	441.0	3730	3760
	483.0	3462	3430
Hg	253.0	18379	18500
	273.0	17430	16800
	293.0	16879	15500
	373.0	15422	12700
	473.0	14446	10100

4. Comparative Analysis of Reported Studies on Liquid Metal Heat Transfer

A number of experiments have been conducted over the years aiming at the heat transfer properties of liquid metals at various temperatures and flow rates. Various scholars have come up with models, experimented and published data to comprehend their thermophysical properties, as well as their convective behaviour better. These works are useful in terms of performance of liquid metals in the broad field of technological applications such as nuclear systems and cooling of electronics. In order to capture the diversity of contributions, Table 4 presents and contrasts the main findings of various researchers and focuses on the differences in the approach, the qualities studied, and the important conclusions made by them.

Table 2: Grashof number ranges and domain of flow of liquid metals from reference [36, 98].

Grashof Number (Gr)	**Flow Domain (in Liquid Metals)**	**Heat Transfer Behaviour**
$Gr < 10^3$	Conduction dominated	Natural convection negligible
$10^3 < Gr < 10^5$	Onset of weak free convection	Small circulation but conduction still dominant
$10^5 < Gr < 10^7$	Onset of measurable convection	Convection begins to dominate heat transfer
$Gr \approx 10^7$ and above	Turbulent convection	Strong buoyancy flow

Table 3: Assessment of liquid metal heat transfer from various studies

Reference	**Fluid**	**Geometry**	**Parameter Range**	**Method**	**Key Findings**
Lyon & Poppendick [48]	Na, Hg	Pipes	Low–medium Grashof	Experimental/ handbook summary	Early systematic studies of liquid-metal heat transfer established baseline data and demonstrated conduction supremacy at low Gr.
Mahony [52]	General liquid metals	Various bodies in fluid	Low Grashof number	Theory/ analysis	Conduction-only models can estimate the disputed heat transfer for suitably low Gr levels.
Azer & Chao [16]	Liquid metals	Pipe/tube flows	Low Pr	Theory/ experimental	A redesigned mixing-length process for turbulent heat transport in liquid metals was proposed.
Fendell [98]	Generic	Isothermal sphere	Small Gr	Analytical	Laminar natural convection around a sphere proved conduction-dominated behaviour and yielded low-Gr asymptotic solutions.
Stewart & Weinberg [81, 82]	Liquid metals	Crustal development setups	Low–moderate Gr	Experimental/ theoretical	Flow structures in liquid metal melts were seen experimentally, and a theoretical companion study was written to examine driving processes.
Kroeger & Ostrach [41]	Pure metals	2D freezing with convection	Solidifying Gr ranges	Numerical	Convection changes the interface during freezing, as demonstrated by coupled solid–liquid models that include modest convection effects.

Table 3 (continued): Assessment of liquid metal heat transfer from various studies

Reference	**Fluid**	**Geometry**	**Parameter Range**	**Method**	**Key Findings**
Singh & Chen [80]	Fluids	Concentric spheres	Moderate Gr	Numerical	Numerical results for free convection between concentric spheres, including flow structure and Nu–Gr data for comparison to experiments.
Dudek et al. [22]	Liquid metals	Spheres	Small Gr	Experimental/ theory	Measured convection heat transfer on low-Gr spheres; theory–experiment comparisons confirmed conduction dominance tendencies.
Wolff et al. [90]	Liquid metals	Vertical cavities	Moderate Gr	Experimental	Extensive natural convection investigations in vertical cavities yield data valuable for validating low-Pr models.
Mohammad & Viskanta [60]	Liquid metals	Various	Low Pr	Modelling/ review	Modelling issues for turbulent buoyant flow in liquid metals were discussed, along with the requirement for modified turbulence closures at low Pr.
Mikityuk [59]	Pb, Na, NaK	Tubes	Wide Gr ranges	Review/data analysis	Compiled statistics and correlations for tube-bundle transfer of heat in liquid metals, as well as engineering correlations for reactor builders.
Ke et al. [36]	Liquid metal	Infinite vertical wall	High Gr	Numerical	Exhibited turbulent natural convection scaling at high Gr; useful as high-Gr benchmarks.
Zwirner et al. [96]	Ga or Ga-based alloys	Laboratory cells	Low–moderate Gr	Experimental	Demonstrated integrated velocity–temperature measuring techniques for low-Pr liquids.
Salyan et al. [74]	Ga	Thermal energy package with metal inserts	System temperature	Experimental	Displayed Ga in metal inserts improves thermal performance and charging/discharging efficiency—a useful heat transfer enhancer.
Zhang et al. [94]	Liquid metals	Manifold microchannel heat sink	Low Pr	Experimental/ numerical	A manifold microchannel design was created employing liquid metal for ultra-high heat flux cooling.
Yao et al. [92]	Ga-based alloys	PCM modules	Low-Pr regime	Review	A summary of current breakthroughs in liquid-metal phase change materials for electronics cooling.

Table 3 (continued): Assessment of liquid metal heat transfer from various studies

Reference	**Fluid**	**Geometry**	**Parameter Range**	**Method**	**Key Findings**
Xie et al. [91]	General liquids	Particle–liquid interface	High Re	Review	Dynamic analysis of a single particle contacting a liquid surface.

Comparisons of several geometries (pipes, spheres, and vertical cavities) show that, while geometry influences local temperature gradients, the dominant conduction mode stays constant under low Gr circumstances. These investigations confirm the unique low-buoyancy, high-conduction behaviour of liquid metals, setting the framework for exact modelling in advanced applications.

5. Emerging applications and geometries

Liquid metals are employed in many new technologies in lacking natural convection which has a small Grashof number, and small systems. Thermal transfer in these situations is conducted and forced through conduction and is not brought about by the buoyant flow. It is important to know the behaviour of liquid metals in such low-Grashof environments in order to develop effective thermal systems.

- The existing electronics and heat exchangers contain narrow channels that reduce the effects of buoyancy. This indicates that flow operates in a low Grashof number. Liquid metals such as gallium and Na-K alloys are able to remove exceptionally large levels of heat because of their speed in heat transport and their smooth flow in these tiny cavities. Nevertheless, such issues as oxidation, clogging, and the compatibility with other materials require consideration.

- Low melting liquid metals including In-Ga-Sn alloys are adopted as thermal interface materials to enhance the heat transfer between surfaces. The distance between surfaces is very low, hence heat conduction is carried out mainly through conduction with low Grashof number. Low-Gr behaviour analysis improves contact performance, reduces corrosion and improves the life of some materials.

- The liquid metal phase transition materials are able to store and dissipate heat in small-scale energy systems. During melting and solidification, the conduction is the principle mode of heat transmission because convection is weak. Knowledge of low Grashof number flow in these materials would allow development of safe and efficient energy storage systems.

6. Conclusion

This review gave a thorough examination of the structure of heat and fluid flow in liquid metals with low Grashof values. The gathered studies show that liquid metals behave differently than typical fluids when convection is weak, owing to their high thermal conductivity and distinctive thermophysical features. At extremely low Grashof numbers, conduction dominates heat transfer, but buoyancy-induced convection progressively alters the flow pattern as Gr rises. The accumulated correlations, experimental data, and numerical analyses emphasize the necessity of precisely describing flow regimes and transport processes for designing dependable systems for nuclear reactors, solar thermal applications, and electronic cooling. Despite significant advances, there are still hurdles in building predictive models that account for the coupled effects of buoyancy, instability, and magnetic fields under actual settings. More systematic practical research and high-fidelity simulations are required to validate theoretical models, especially in mini- and microchannel systems where liquid metals are increasingly being used.

In conclusion, liquid metals have a high potential as heat transfer medium in next-generation thermal systems, provided that their low Grashof number behaviour is well understood and precisely characterized. To fully exploit the benefits of liquid-metal-based cooling systems, future research should focus on connecting experimental data with sophisticated simulations, improving design techniques, and resolving material compatibility and safety concerns.

Acknowledgements

The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number **(2025/RV/14)**.

Author Contributions

All authors have equal work. All authors have read and agreed to the published version of the manuscript.

Funding

The authors extend their appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number **(2025/RV/14)**.

Data Availability Statement

Data available upon request.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] A. Ahmad, R. Nawaz, A. Ali, and A. D. Alruwaili. Impact of microorganisms on blasius–rayleigh–stokes flow and heat transfer of nanofluid: A numerical study. *ZAMM—Journal of Applied Mathematics and Mechanics / Zeitschrift für Angewandte Mathematik und Mechanik*, 104(12):e202300287, 2024.

[2] R. Akhmedagaev, O. Zikanov, and Y. Listratov. Magnetoconvection in a horizontal duct flow at very high hartmann and grashof numbers. *Journal of Fluid Mechanics*, 931:A29, 2022.

[3] A. Ali, M. Ahmed, A. Ahmad, and R. Nawaz. Enhanced heat transfer analysis of hybrid nanofluid over a riga plate: incorporating lorentz forces and entropy generation. *Tribology International*, 188:108844, 2023.

[4] A. Ali, Y. Ali, P. Kumam, K. Babar, A. Ahmed, and Z. Shah. Flow of a nanofluid and heat transfer in channel with contracting/expanding walls. *IEEE Access*, 7:102427–102436, 2019.

[5] A. Ali, F. Iqbal, D. N. Khan Marwat, S. Asghar, and M. Awais. Soret and dufour effects between two rectangular plane walls with heat source/sink. *Heat Transfer—Asian Research*, 49(1):614–625, 2020.

[6] A. Ali, R. Khatoon, M. Ashraf, and M. Awais. Cattaneo–christov heat flux on mhd flow of hybrid nanofluid across stretched cylinder with radiations and joule heating effects. *Waves in Random and Complex Media*, pages 1–18, 2022.

[7] A. Ali, M. Maqsood, H. J. Anjum, M. Awais, and M. Sulaiman. Analysis of heat transfer on mhd jeffrey nanofluid flow over nonlinear elongating surface of variable thickness. *ZAMM—Journal of Applied Mathematics and Mechanics / Zeitschrift für Angewandte Mathematik und Mechanik*, 102(2):e202100250, 2022.

[8] A. Ali, D. N. K. Marwat, and A. Ali. Analysis of flow and heat transfer over stretching/shrinking and porous surfaces. *Journal of Plastic Film & Sheeting*, 38(1):21–45, 2022.

[9] A. Ali, A. Noreen, S. Saleem, A. F. Aljohani, and M. Awais. Heat transfer analysis of cu–al_2o_3 hybrid nanofluid with heat flux and viscous dissipation. *Journal of Thermal Analysis & Calorimetry*, 143(3), 2021.

[10] A. Ali, Z. Shah, S. Mumraiz, P. Kumam, and M. Awais. Entropy generation on mhd peristaltic flow of cu-water nanofluid with slip conditions. *Heat Transfer—Asian Research*, 48(8):4301–4319, 2019.

[11] K. An, Z. Su, M. Zhang, and Y. Deng. Liquid metal-based micro/mini-channel heat transfer: Progress, challenges, and opportunities. *Applied Thermal Engineering*, page 123551, 2024.

[12] M. Ashraf. Mini review on thermophysical properties of heat and fluid flow: As-

sessing environmental impacts and implications. *Computational Environmental Heat Transfer*, 1(1):1–5, 2025.

[13] M. Ashraf, A. Abbas, A. Ali, Z. Shah, H. Alrabaiah, and E. Bonyah. Numerical simulation of the combined effects of thermophoretic motion and variable thermal conductivity on free convection heat transfer. *AIP Advances*, 10(8), 2020.

[14] M. Ashraf, A. Ilyas, Z. Ullah, and A. Ali. Combined effects of viscous dissipation and magnetohydrodynamic on periodic heat transfer along a cone embedded in porous medium. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 236(6):2325–2335, 2022.

[15] M. Azad, D. Groulx, and A. Donaldson. Natural convection onset during melting of phase change materials: Part ii–effects of fourier, grashof, and rayleigh numbers. *International Journal of Thermal Sciences*, 170:107062, 2021.

[16] N. Z. Azer and B. T. Chao. A mechanism of turbulent heat transfer in liquid metals. *International Journal of Heat and Mass Transfer*, 1(2-3):121–138, 1960.

[17] R. Benderradji, H. Gouidmi, D. Taloub, and A. Beghidja. Numerical study three-dimensional of mixed convection in a cavity: Influence of reynolds and grashof numbers. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, 51(1):42–52, 2018.

[18] R. Benderradji, M. Brahimi, and F. Khalfallah. Numerical study of heat transfer by mixed convection in a cavity filled with nanofluid: Influence of reynolds and grashof numbers. *International Journal of Applied Mathematics Computational Science and Systems Engineering*, 4:77–86, 2022.

[19] X. Y. Chen, J. C. Yang, and M. J. Ni. Effects of horizontal magnetic fields on flow morphologies and global transports in liquid metal thermal convection. *Journal of Fluid Mechanics*, 1000:A59, 2024.

[20] H. K. Dawood, H. A. Mohammed, N. A. C. Sidik, K. M. Munisamy, and M. A. Wahid. Forced, natural and mixed-convection heat transfer and fluid flow in annulus: A review. *International Communications in Heat and Mass Transfer*, 62:45–57, 2015.

[21] Y. Deng, Y. Jiang, and J. Liu. Low-melting-point liquid metal convective heat transfer: A review. *Applied Thermal Engineering*, 193:117021, 2021.

[22] D. R. Dudek, T. H. Fletcher, J. P. Longwell, and A. F. Sarofim. Natural convection induced drag forces on spheres at low grashof numbers: comparison of theory with experiment. *International Journal of Heat and Mass Transfer*, 31(4):863–873, 1988.

[23] D. Frazer, E. Stergar, C. Cionea, and P. Hosemann. Liquid metal as a heat transport fluid for thermal solar power applications. *Energy Procedia*, 49:627–636, 2014.

[24] A. Fritsch, J. Flesch, V. Geza, C. Singer, R. Uhlig, and B. Hoffschmidt. Conceptual study of central receiver systems with liquid metals as efficient heat transfer fluids. *Energy Procedia*, 69:644–653, 2015.

[25] R. Fusaro, D. Ferretto, N. Viola, R. Scigliano, V. De Simone, and M. Marini. Liquid metals heat-pipe solution for hypersonic air-intake leading edge: Conceptual design, numerical analysis and verification. *Acta Astronautica*, 197:336–352, 2022.

[26] P. Ganeshkumar, S. Vinothkumar, P. Sundaram, A. Sathishkumar, S. C. Kim, V. Ramkumar, and K. E. Alzahrani. Performance evaluation of shot-blasted heat

exchangers with mwcnt and activated carbon nanofluids: assessing entropy, exergy, sustainability index, grashof, rayleigh, and richardson numbers for solar thermal applications. *Journal of Thermal Analysis and Calorimetry*, 149(22):13285–13308, 2024.

[27] C. Ghernoug, M. Djezzar, and A. Bouras. The natural convection in annular space located between two horizontal eccentric cylinders: The grashof number effect. *Energy Procedia*, 36:293–302, 2013.

[28] M. G. Giometto, G. G. Katul, J. Fang, and M. B. Parlange. Direct numerical simulation of turbulent slope flows up to grashof number. *Journal of Fluid Mechanics*, 829:589–620, 2017.

[29] W. Guo, A. Shams, Y. Sato, and B. Niceno. Influence of buoyancy in a mixed convection liquid metal flow for a horizontal channel configuration. *International Journal of Heat and Fluid Flow*, 85:108630, 2020.

[30] A. Heinzel, W. Hering, J. Konys, L. Marocco, K. Litfin, G. Müller, and T. Wetzel. Liquid metals as efficient high-temperature heat-transport fluids. *Energy Technology*, 5(7):1026–1036, 2017.

[31] J. Hu. Linear global stability of a downward flow of liquid metal in a vertical duct under strong wall heating and transverse magnetic field. *Physical Review Fluids*, 6(7):073502, 2021.

[32] W. Jaeger and W. Hering. Mixed convection with liquid metals: review of experiments and model development. In *Proceedings of the Advances in Thermal Hydraulics (ATH)*, pages 846–859, 2018.

[33] O. M. Kamiyo, D. Angeli, G. S. Barozzi, M. W. Collins, V. O. S. Olunloyo, and S. O. Talabi. A comprehensive review of natural convection in triangular enclosures. *Applied Mechanics Reviews*, 63(6):060801, 2010.

[34] C. Karcher, Y. Kolesnikov, O. Andreev, and A. Thess. Natural convection in a liquid metal heated from above and influenced by a magnetic field. *European Journal of Mechanics - B/Fluids*, 21(1):75–90, 2002.

[35] C. Karcher, Y. Kolesnikov, O. Andreev, and A. Thess. Natural convection in a liquid metal heated from above and influenced by a magnetic field. *European Journal of Mechanics - B/Fluids*, 21(1):75–90, 2002.

[36] J. Ke, N. Williamson, S. W. Armfield, A. Komiya, and S. E. Norris. High grashof number turbulent natural convection on an infinite vertical wall. *Journal of Fluid Mechanics*, 929:A15, 2021.

[37] A. Khan, M. Ashraf, A. M. Rashad, and H. A. Nabwey. Impact of heat generation on magneto-nanofluid free convection flow about sphere in the plume region. *Mathematics*, 8(11):2010, 2020.

[38] K. Khanafer. Comparison of flow and heat transfer characteristics in a lid-driven cavity between flexible and modified geometry of a heated bottom wall. *International Journal of Heat and Mass Transfer*, 78:1032–1041, 2014.

[39] D. Y. Kim, H. S. Yoon, and M. Y. Ha. Particle behavior in a vertical channel with thermal convection in the low grashof number regime. *Computers & Fluids*, 48(1):183–191, 2011.

[40] P. Kiš and H. Herwig. Natural convection in a vertical plane channel: Dns results for

high grashof numbers. *Heat and Mass Transfer*, 50(7):957–972, 2014.

[41] P. G. Kroeger and S. Ostrach. The solution of a two-dimensional freezing problem including convection effects in the liquid region. *International Journal of Heat and Mass Transfer*, 17(10):1191–1207, 1974.

[42] V. N. Kurdyumov and A. Linan. Free convection from a point source of heat, and heat transfer from spheres at small grashof numbers. *International Journal of Heat and Mass Transfer*, 42(20):3849–3860, 1999.

[43] F. C. Li, T. Kunugi, and A. Serizawa. Mhd effect on flow structures and heat transfer characteristics of liquid metal–gas annular flow in a vertical pipe. *International Journal of Heat and Mass Transfer*, 48(12):2571–2581, 2005.

[44] X. F. Li, X. J. Wang, and Z. Z. Li. Grashof number effects on nanofluids in natural convection heat transfer. *Applied Mechanics and Materials*, 468:43–48, 2014.

[45] G. L. Liu and J. Liu. Convective cooling of compact electronic devices via liquid metals with low melting points. *Journal of Heat Transfer*, 143(5):050801, 2021.

[46] R. Liu, H. Zhang, M. Nie, L. Yao, X. Li, and F. Li. Numerical investigation on the heat transfer performance of the liquid metal array jet impingement. *International Journal of Thermal Sciences*, 210:109674, 2025.

[47] N. Lorenzin and A. Abanades. A review on the application of liquid metals as heat transfer fluid in concentrated solar power technologies. *International Journal of Hydrogen Energy*, 41(17):6990–6995, 2016.

[48] R. N. Lyon and H. Poppendiek. *Liquid-metal heat transfer*. 1951.

[49] B. Lyu, L. Bühler, C. Koehly, and C. Mistrangelo. 3d magneto-convective instabilities of liquid metal flow in a generic geometry related to wcll blankets. *Fusion Engineering and Design*, 217:115113, 2025.

[50] H. Ma, W. Lu, W. Zhou, Z. Ding, X. Lü, Y. Cao, and N. Deng. Effects of rotation on the trailing vortex and heat transfer from a horizontal rotating cylinder at higher grashof number. *International Communications in Heat and Mass Transfer*, 68:20–26, 2015.

[51] K. Ma and J. Liu. Liquid metal cooling in thermal management of computer chips. *Frontiers of Energy and Power Engineering in China*, 1(4):384–402, 2007.

[52] J. J. Mahony. Heat transfer at small grashof numbers. *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, 238(1214):412–423, 1957.

[53] L. Marocco, A. Loges, T. Wetzel, and R. Stieglitz. Experimental investigation of the turbulent heavy liquid metal heat transfer in the thermal entry region of a vertical annulus with constant heat flux on the inner surface. *International Journal of Heat and Mass Transfer*, 55(23-24):6435–6445, 2012.

[54] G. D. McBain and D. W. Stephens. Low grashof number convective heat transfer across a spherical cavity. In *Heat and Mass Transfer Australasia*, pages 231–237, 2000.

[55] F. Mebarek-Oudina and R. Bessaïh. Oscillatory magnetohydrodynamic natural convection of liquid metal between vertical coaxial cylinders. *Journal of Applied Fluid Mechanics*, 9(4):1655–1665, 2016.

[56] J. P. Medrado. *Evaporation from Air-Water Interfaces at Very Low Grashof Numbers*.

PhD thesis, University of California, San Diego, 2021.

[57] J. P. Medrado, R. H. Inman, and C. F. Coimbra. Pool evaporation under low grashof number downward convection. *International Journal of Heat and Mass Transfer*, 181:122021, 2021.

[58] G. M. Mikhailov, V. G. Mikhailov, L. A. Kondakova, and L. S. Reva. Determination of the coefficient of convective heat transfer in a transient pipe flow at high grashof numbers. *Theoretical Foundations of Chemical Engineering*, 41(4):414–416, 2007.

[59] K. Mikityuk. Heat transfer to liquid metal: review of data and correlations for tube bundles. *Nuclear Engineering and Design*, 239(4):680–687, 2009.

[60] A. A. Mohamad and R. Viskanta. Modeling of turbulent buoyant flow and heat transfer in liquid metals. *International Journal of Heat and Mass Transfer*, 36(11):2815–2826, 1993.

[61] P. P. Moniaga, I. I. Hakim, M. Juarsa, and P. H. Setiawan. Reynolds and grashof numbers analysis on steady state natural circulation flow using fassip-02 large scale test loop. In *Journal of Physics: Conference Series*, volume 2972, page 012022. IOP Publishing, March 2025.

[62] B. Moundjia and Z. Samah. Numerical simulation of free convection in porous media modeled by darcy-brinkman equation at low grashof numbers. *International Journal of Heat & Technology*, 41(2), 2023.

[63] A. Muhammad. A comprehensive review of the impact of thermal radiations on energy exchange systems. *The Nucleus*, 60(1):108–111, 2023.

[64] A. Muhammad, S. Asghar, Z. Syed, and M. A. Hossain. Natural convection heat transfer past a magnetized vertical permeable plate for liquid metals. *Middle East Journal of Scientific Research*, 13(8):983–992, 2013.

[65] H. A. Nabwey, M. Ashraf, H. Nadeem, A. M. Rashad, and A. J. Chamkha. Optimizing renewable energy systems: A comprehensive review of entropy generation minimization. *AIP Advances*, 14(12), 2024.

[66] H. A. Nabwey, M. Ashraf, and A. M. Rashad. A comprehensive review of convective heat transfer in humid air and its physical perspectives in climate change. *AIP Advances*, 15(5), 2025.

[67] D. A. Ognerubov and Y. I. Listratov. An investigation into the effect of prandtl number on heat transfer in a liquid metal flow in a round tube at a constant peclet number. *Thermal Engineering*, 71(12):1076–1082, 2024.

[68] M. Oyinloye, S. Sreedharan, M. Al-Juaied, S. Michaux, M. Guerra, M. Burks Magara, and W. Roberts. Dynamics of co2 desublimation for enhanced carbon capture: A study of reynolds and grashof number impact. *SSRN Electronic Journal*, 2024. Available at SSRN 5010615.

[69] J. Pacio, L. U. C. A. Marocco, and T. Wetzel. Review of data and correlations for turbulent forced convective heat transfer of liquid metals in pipes. *Heat and Mass Transfer*, 51:153–164, 2015.

[70] J. Pacio and T. Wetzel. Assessment of liquid metal technology status and research paths for their use as efficient heat transfer fluids in solar central receiver systems. *Solar Energy*, 93:11–22, 2013.

[71] H. Qiu, J. Li, Z. Dong, M. Wang, W. Tian, and G. H. Su. Numerical study on inter-wrapper flow and heat transfer characteristics in liquid metal-cooled fast reactors. *Progress in Nuclear Energy*, 155:104534, 2023.

[72] A. Rahimi, A. Dehghan Saee, A. Kasaeipoor, and E. Hasani Malekshah. A comprehensive review on natural convection flow and heat transfer: the most practical geometries for engineering applications. *International Journal of Numerical Methods for Heat & Fluid Flow*, 29(3):834–877, 2019.

[73] J. Rong, Y. Huang, Z. Li, W. Wang, J. Guo, and S. Guo. Experimental study of airflow thermal fluctuation properties induced by liquid metal pouring based on schlieren and proper orthogonal decomposition. *Thermal Science and Engineering Progress*, 47:102266, 2024.

[74] S. Salyan, B. Praveen, H. Singh, S. Suresh, and A. S. Reddy. Liquid metal gallium in metal inserts for solar thermal energy storage: a novel heat transfer enhancement technique. *Solar Energy Materials and Solar Cells*, 208:110365, 2020.

[75] R. Samanta and H. Chattopadhyay. Study of thermal convection in liquid metal using modified lattice boltzmann method. *International Journal of Numerical Methods for Heat & Fluid Flow*, 35(4):1397–1425, 2025.

[76] M. T. Sarowar. Numerical analysis of a liquefied metal cooled mini channel heat sink with five different ceramic substrates. *Ceramics International*, 47(1):214–225, 2021.

[77] N. A. Shah, I. L. Animasaun, R. O. Ibraheem, H. A. Babatunde, N. Sandeep, and I. Pop. Scrutinization of the effects of grashof number on the flow of different fluids driven by convection over various surfaces. *Journal of Molecular Liquids*, 249:980–990, 2018.

[78] Y. Shen and O. Zikanov. Thermal convection in a liquid metal battery. *Theoretical and Computational Fluid Dynamics*, 30:275–294, 2016.

[79] A. Shevaladze, E. Putra, P. H. Setiawan, H. A. Gunawan, and M. Juarsa. Analysis of grashof number in large-scale passive cooling systems based on temperature changes. In *Proceeding of International Conference on Multidisciplinary Research*, volume 7, pages 225–234, February 2025.

[80] S. N. Singh and J. Chen. Numerical solution for free convection between concentric spheres at moderate grashof numbers. *Numerical Heat Transfer*, 3(4):441–459, 1980.

[81] M. J. Stewart and F. Weinberg. Fluid flow in liquid metals: Experimental observations. *Journal of Crystal Growth*, 12(3):228–238, 1972.

[82] M. J. Stewart and F. Weinberg. Fluid flow in liquid metals: I. theoretical analysis. *Journal of Crystal Growth*, 12(3):217–227, 1972.

[83] P. Suri, A. Verma, S. A. Patel, and R. P. Chhabra. Free convection from a single and a pair of spheres in power-law fluids at very small grashof numbers. *Journal of Non-Newtonian Fluid Mechanics*, 320:105109, 2023.

[84] Z. Tian, C. Wang, K. Guo, D. Zhang, G. H. Su, W. Tian, and S. Qiu. A review of liquid metal high temperature heat pipes: Theoretical model, design, and application. *International Journal of Heat and Mass Transfer*, 214:124434, 2023.

[85] Z. Ullah, M. Ashraf, I. E. Sarris, and T. E. Karakasidis. The impact of reduced gravity on oscillatory mixed convective heat transfer around a non-conducting heated

circular cylinder. *Applied Sciences*, 12(10):5081, 2022.

[86] G. Wang. A review of research progress in heat exchanger tube rupture accident of heavy liquid metal cooled reactors. *Annals of Nuclear Energy*, 109:1–8, 2017.

[87] S. Wang, X. Zhao, J. Luo, L. Zhuang, and D. Zou. Liquid metal (lm) and its composites in thermal management. *Composites Part A: Applied Science and Manufacturing*, 163:107216, 2022.

[88] X. Wang, C. Lu, and W. Rao. Liquid metal-based thermal interface materials with a high thermal conductivity for electronic cooling and bioheat-transfer applications. *Applied Thermal Engineering*, 192:116937, 2021.

[89] Z. H. Wang and Z. K. Zhou. External natural convection heat transfer of liquid metal under the influence of the magnetic field. *International Journal of Heat and Mass Transfer*, 134:175–184, 2019.

[90] F. Wolff, C. Beckermann, and R. Viskanta. Natural convection of liquid metals in vertical cavities. *Experimental Thermal and Fluid Science*, 1(1):83–91, 1988.

[91] J. Xie, L. Hou, T. Yang, and R. Li. A comprehensive review of research on the motion behavior and liquid flow dynamics of a single particle impacting a liquid surface. *Physics of Fluids*, 37(3), 2025.

[92] Y. Yao, W. Li, J. Liu, and Z. Deng. Liquid metal phase change materials for thermal management of electronics. *Advances in Physics: X*, 9(1):2324910, 2024.

[93] M. Zhang, Q. Gao, Z. Zhao, L. Guo, X. Li, C. Zhang, and W. Rao. Liquid metal manifold microchannel heat sink for ultra-high heat flux cooling. *Applied Thermal Engineering*, 248:123117, 2024.

[94] X. D. Zhang. Analytical and computational heat transfer of single-phase liquid metal. In *Handbook of Liquid Metals*, pages 1–51. Springer Nature Singapore, Singapore, 2024.

[95] T. Zürner, F. Schindler, T. Vogt, S. Eckert, and J. Schumacher. Combined measurement of velocity and temperature in liquid metal convection. *Journal of Fluid Mechanics*, 876:1108–1128, 2019.

[96] L. Zwirner, R. Khalilov, I. Kolesnichenko, A. Mamykin, S. Mandrykin, A. Pavlinov, and O. Shishkina. The influence of the cell inclination on the heat transport and large-scale circulation in liquid metal convection. *Journal of Fluid Mechanics*, 884:A18, 2020.

[97] W. Kim and T. Chair. A simplified phenomenological theory of viscosity for liquid metals. *Bulletin of the Korean Chemical Society*, 22(1):43–45, 2001.

[98] F. E. Fendell. Laminar natural convection about an isothermally heated sphere at small grashof number. *Journal of Fluid Mechanics*, 34(1):163–176, 1968.