Microscale Thermal Management: A Review of Nanofluid Applications in Microfluidic Channels

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ABSTRACT

This critical review study focuses on the integration of nanofluids with microfluidic channels. This emerging field, which combines nanotechnology and microfluidics, has the potential to transform the control of temperatures and monitoring completely. Nanofluids, which are fluids containing nanoparticles like metals or oxides, greatly improve the heat management capabilities of base fluids. These materials are highly efficient in transferring and conducting heat, making them ideal for applications such as cooling electronics and medical diagnostics. The addition of nanofluids to microfluidic routes, typically measured in micrometers, greatly simplifies fluid flow and heat transfer regulation. The article includes several research studies demonstrating how nanofluids enhance the performance of microfluidic systems compared to conventional fluids. The benefits are examined, including the potential for reduced size and increased energy efficiency of heat exchanges and cooling systems. As a result, these technologies are better suited for implementation in the healthcare and industry sectors.

Keywords-microfluidic channel; nanofluid; viscosity; thermal conductivity

I. INTRODUCTION

The form heterogeneous discipline is known as microfluidics because it combines the field of fluid dynamics as well as microelectronics, materials science, chemistry, biology, and physics. A wide range of materials can produce tiny crisps for crystallizing microsystems. They can be manufactured to fit profiles and configurations that conform to formative shapes and sizes organized with flexibility, robustness, modularity proficiency, and the ability to take them apart and reassemble them. These crisps can be used alone or with devices for generating nanoparticles, soaking up medications, transmitting medications to targeted phases, finding reversible cells, measuring working and developing cells, and enabling diagnostics [1].

The base fluid is the central term in the function of microfluidic products. The fluid behaves as isothermal, implying it is the most constant medium to transport other substances or reagents. The main ingredients included in the fluid absorbents are oils, water, and chemical solvents. The choice of fluid depends on the reactivity with other substances and their endurance and reaction at different temperatures [2]. Nanofluids can only be created by blending nanoparticles, often metals, oxides, or carbon nanotubes, with a base fluid. Each suspension has specific mechanical, electrical, and thermal properties not present in the original liquid or each nanoparticle. When nanoparticles are added to a fluid flowing in a microfluidic channel, it is possible to achieve significant changes in the actions of the fluid, leading to extreme improvements in the reaction kinetics and the process of heat transfer [3]. Many studies have focused on the integration of nanofluids into microfluidic channels. Authors in [4] conducted experiments on applying magnetic nanofluids in microfluidic devices to provide accurate control and manipulation of fluids. This breakthrough has enabled the development of personalized drug delivery systems. The coupling of nanofluids with the simplified flow properties of microfluidics has led to the development of novel sensing and molecular separation applications.

This review paper aims to summarize the recent advancements through a proper study of available information regarding the utilization of nanofluids within microfluidic channels. While microchannels have had many uses, the case studies of nanofluids have not adequately studied this technology. This literature review examined only the cases of microchannel devices that use nanofluids. The goal is to thoroughly understand the nanofluid's behavior in a microfluidic channel.

II. NANOFLUID

Nanofluids are liquids that include nanoparticles, i.e. particles with diameters in the nanometer range. The particles consist of metals, oxides, carbides, or carbon nanotubes. Oil, water, ethylene glycol, and base fluids are the most commonly used heat transfer fluids. The main objective of distributing nanoparticles into the selected base fluid is to enhance and boost its thermal characteristics [5]. The improved heat conductivity shown by nanofluids compared to base fluids is a significant benefit. Nanoparticles such as copper, aluminum, and silver exhibit enhanced thermal conductivities when mixed with fluids compared to the fluids alone. The overall thermal conductivity of the fluid increases when these particles are uniformly distributed throughout it due to the Brownian motion of the nanoparticles. This property is beneficial for applications that need effective heat transport, such as cooling systems for electronics or motors [6].

Nanofluids are commonly utilized in various application domains where maximizing heat transfer efficiency is crucial. Common applications of nanofluids include cooling electronics, automotive and aircraft cooling systems, and the operation of renewable energy systems such as fuel cells and solar panels. The potential advantage of the new fluids lies in their ability to increase efficiency and decrease the size and cost in certain thermal engineering systems, which may persist for many years. In order to foster innovation in the fields of thermal engineering and material science, it is imperative to conduct further research and utilize them to a greater extent [7]. Producing nanofluids can be done using one-step or two-step methods [16]. The one-step method creates nanofluids directly by spreading them out in the base fluid directly whereas the two-step method starts with the base fluid and then disperses the nanoparticles uniformly by hot plate stirring and sonication.

In the one-step approach, the preparation is user-friendly, and it may form very stable nanofluids [8]. The technique is advantageous when creating nanofluids with characteristics necessary for translating into unique areas, such as lubrication, medical diagnostics, and thermal regulation. Microwave radiation can be utilized in the one-step approach [9]. Copper and silver nanofluids may be created using this approach: microwave radiation is utilized to reduce the production of the produced metal salt in ethylene glycol or mineral oil, among other solvents. The merit is that it maintains the stable behavior of nanofluids and bounds particle size restriction [10]. Compression is the method used to generate solid nanophase powders from the gaseous phase. Liquid with a low vapor pressure is constantly poured into a compressor. Nanoparticles are made by either liquid chemical or Physical Vapor Deposition (PVD) [11]. PVD applies a thin material coating to a workpiece by condensing vaporized material with a vacuum. PVD includes enhanced cathode arc deposition, sputtering, ion plating, evaporative deposition, and electron beam physical vapor deposition. The sputtering or hot source PVD process vaporizes solid coating material using heat or ablation.

The two-step method [12] is extensively used due to its user-friendly nature and ability to generate consistent and uniform nanofluids utilizing various base fluids. Initially, the first stage involves generating desiccated nanoparticles by conventional particle fabrication methods. These methods may include chemical vapor deposition, sol-gel processes, and ball milling. The specific attributes and composition of the nanoparticles dictate the most suitable technique. For nanoparticles to achieve dispersion in the base fluid, they must possess exact dimensions, geometry, and surface properties [13]. The second phase of producing nanofluids is characterized by the homogenous incorporation of nanoparticles into the selected base fluid. Nanofluids are liquid and can be made with either water or ethylene glycol, oil, or any other fluid [14]. In the dispersion stage, which incorporates mechanical agitation, ultrasonication, or high-shear mixing to disintegrate and disperse nanoparticle clusters, the two-step technique has a significant advantage from the extensive range of base fluids and nanoparticles. As a result, the properties of nanofluids change and better respond to specific requirements. This process is as accessible to users and is no less expensive than others, such as the one-step process. Two-step-processed nanofluids are used to improve oil extraction, electronics cooling, pharmaceutical manufacturing, and solar energy systems [15]. Due to their superior thermal characteristics, nanofluids are essential in situations that require high heat conduction. The two-step process is crucial for producing nanofluids, allowing engineers and scientists to take advantage of nanoparticles' distinctive properties to improve fluid technologies.

III. THERMAL CONDUCTIVITY

There are several ways to enhance the thermal conductivity properties of a nanofluid. The type, size and the geometric shape of the nanoparticles play significant roles in changing the thermal properties of the liquid into which they are incorporated. Metal oxide nanoparticles such as titanium oxide and zinc oxide have been used widely and employed significantly as they are successfully heat-efficient and conductive [5]. Due to their shape, the particles are asymmetrical, dramatically affecting the movement caused by Brown’s discipline and the heat energy transmitted. The uniformity of their distribution and method of preparation affects their thermal conduction. This improvement results from an excess in the kinetic energy of the particles, resulting from a higher outcome of collisions and energy exchanges. When nanoparticle combinations are attempted, several different nanoparticles have been shown to increase the thermal conductivity of nanofluids. Fluids with different nanoparticles transmit heat more effectively than fluids with one type of nanoparticle [13]. The process of increasing thermal conductivity in nanofluids is intricate and relies on the characteristics of the nanoparticles, the fluid medium, and the ambient conditions. Nanofluids exhibit exceptional versatility, with the capacity to significantly modify the design and properties of heat management systems. Solid nanoparticles exhibit higher thermal conductivity than fluids, resulting in enhanced efficiency and thermal conductivity.

IV. VISCOSITY

The other scope connected to the increased number of nanoparticles in a nanofluid is raising its viscosity. This procedure is conditioned by the enhanced resistance of a fluid to the relative alteration of part identified places, or, in other words, by the increasing the capability of the particle to dampen the dynamics of other particles [17]. Several studies demonstrate that nanofluids reveal a notable relationship between the viscosity and the number of nanoparticles. As viscosity increases, the fluid's consistency intensifies and its ability to be deformed decreases. The heightened resistance necessitates a greater amount of force to propel the fluid through a system at an equivalent pace. Therefore, increased viscosity requires more power to be pumped to the fluid flow within the system. This detail is vital because higher viscosity implies a more significant difference in pressure in the system and, thus, more energy consumed while pumping nanofluids [18].

Nanoparticles embedded into heat exchangers play the same role in increasing the power relevant to pumping the fluid, decreasing the system's energy efficiency. This is best when the drain pattern is significant, thus, it is related to turbulent or laminar flow. Furthermore, there is a noticeable power increase as the nanofluid concentration rises. In turn, the correlation is not linear and promotes a practical peak of enhanced energy expenditures when the fluid has sufficient nanoparticles. The molecular significance lies in the requirement to achieve a balance between the heat exchange capability and the viscosity parameter. Hence, it is imperative to be aware of these unique characteristics to optimize the use of this fluid in various industrial and automotive applications.

V. HEAT TRANSFER PROPERTIES OF NANOFLUIDS

Compared to regular heat transfer fluids, nanofluids have much better heat transfer qualities. The main reason for the improvements is that nanofluids have better thermal conductivity and convection heat transfer coefficients [19]. Another intriguing feature regarding the reaction of nanofluids to magnetic fields is the creation of magnetic nanofluids when magnetic particles, including iron, nickel, or cobalt oxides, are added to a liquid base. However, when influenced by magnetic fields, they reveal heat transfer features. Therefore, a magnetic field may stimulate heat transfer due to the fluid flow effect or improve the fluid's thermal conductivity. Nevertheless, possible outcomes can vary significantly depending on the experiment's conditions and individual nanofluids' characteristics.

Alternatively, the methods of preparation of nanofluids also determine the stability and uniformity of nanoparticle dispersion, collectively influencing its thermal properties [20].

VI. MICROFLUIDIC CHANNEL

The microfluidic channel is a critical element of microfluidic systems that is a set of miniature tools designed to work with minimal volumes of fluids, ranging from millimeters to micrometers [21]. These devices are used in various scientific areas, including chemistry, biology, medicine, and engineering. They are characterized by multiple benefits compared to traditional laboratory methods. Microfluidic systems consume fewer reagents, have faster processing speeds, and can be automated and integrated. The design of a microfluidic channel is relatively thin, with the diameter typically ranging from tens to hundreds of micrometers. Microfluidic channel designs are integrated into a substrate material, with some common alternatives being silicon, glass, or polymers like polydimethylsiloxane (PDMS) [22, 23]. The channel layouts could vary from straight to winding or branching, among other possible configurations. Microfluidic channels are important due to their ability to revolutionize the miniaturization and integration of laboratory processes, thereby potentially improving various research and development domains.

VII. PREVIOUS STUDIES ON MICROFLUIDIC CHANNELS

To make the flow uniform in a Mini Cross-flow Heat Exchanger (MCHE), authors in [24] experimented on distributors. They compared structural distributors, pyramid distributors, and micro cross-flow heat exchangers for thermal efficiency and pressure drop. They found that distributors improve thermal efficiency by allowing fluid circulation, although at higher pressures. Compared to the other designs considered, the traditional pyramid distributor and outlet with structural collector demonstrated superior thermal performance and a lesser pressure drop.

A micro-cross flow heat exchanger that used water was the research subject in [25]. The theoretical framework was constructed and confirmed by comparing the theoretical findings with the experimental data from the literature. The analysis results showed that the average temperature of the hot and cold flows significantly impacts the heat transfer and pressure reduction rate. Higher average temperature increases the heat transfer rate when the efficiency remains constant. Nonetheless, the pressure drop and heat transfer rate decrease as the effectiveness increases, although their efficacy differs. Authors in [26] showed that the uniformity of the flow in the channels is mainly determined by the design of the manifolds, the placement and length of the inlet and outlet points, and the speed at which the fluid is introduced through the inlet. The experimental results indicated that including a microchannel significantly impacts the speed of heat transfer without regard to flow rates. The phenomena may be caused by laminar flow, heat transfer by conduction in the channel walls, fluid contact with channel walls, and micro convection.

VIII. NANOFLUIDS IN MICROFLUIDIC CHANNELS

Authors in [27] examined experimentally the efficiency of a copper heat sink with rectangular microchannels under smooth flow circumstances. According to the results of their study, the use of nanofluid in place of deionized water results in an increase in the heating capacity of the microchannel. With the use of nanofluid in the system, it was seen that there was a little increase in pressure drop, friction factor, and fouling thermal resistance parameter. This is a significant finding. As nanofluid flow rate and mass concentration increased, the Microchannel Heat Sink (MCHS) heat transfer coefficient and pressure drop increased.

In [28], mixtures of CuO nanoparticles and H_2O was used as cooling agents in a MCHS to assess its effectiveness, without a dispersal agent. Their study revealed that utilizing nanofluids exhibited better heat absorption abilities than water-cooled MCHS at low flow rates. Nevertheless, heat exchange was primarily impacted by the fluid flow rate at elevated flow velocities, while nanoparticles had little impact. Increasing the nanofluid's temperature hindered the formation of larger clusters by the particles clumping together. It was noticed that the presence of nanoparticles led to a modest rise in pressure, which contributed to the pressure drop.

IX. CONCLUSION

In conclusion, the current review of nanofluids for microfluidic systems shows significant progress in this domain that links microfluidics, nanotechnology, and thermal engineering. Nanoparticle-enhanced microfluidic devices improve fluidic manipulation, thermal conductance, and heat transfer. Such systems make power generation, human body detection, and electronic cooling possible. Due to their unique properties, nanofluids improve microchannel heat transfer. Some obstacles must be overcome to use these changes effectively. Nanoparticle distribution uniformity and microchannel obstructions have been addressed. To maximise nanofluids' fluid dynamics and heat transfer potential, these two elements must be in equilibrium. To improve nanofluid durability and stability, this paper suggests more nanoparticle synthesis and dispersion research. Understanding fluids' non-Newtonian properties may help explain system performance and fluid flow. Increased use of nanofluids in microfluidic channels will improve microscale technologies and expand the field. Scientists and other professionals can overcome these obstacles and improve nanofluids using the existing knowledge. Innovative methods will achieve heat control and other goals.

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REFERENCES

[1] S. Chen *et al.*, "Present status of microfluidic PCR chip in nucleic acid detection and future perspective," *TrAC Trends in Analytical Chemistry*, vol. 157, Dec. 2022, Art. no. 116737, https://doi.org/10.1016/j.trac.2022.116737.

[2] S. F. Wright, I. Zadrazil, and C. N. Markides, "A review of solid–fluid selection options for optical-based measurements in single-phase liquid, two-phase liquid–liquid and multiphase solid–liquid flows," *Experiments in Fluids*, vol. 58, no. 9, Aug. 2017, Art. no. 108, https://doi.org/10.1007/s00348-017-2386-y.

[3] M. Danikas, "Breakdown in Nanofluids: A Short Review on Experimental Results and Related Mechanisms," *Engineering, Technology & Applied Science Research*, vol. 8, no. 5, pp. 3300–3309, Oct. 2018, https://doi.org/10.48084/etasr.2136.

[4] V. A. Roodan *et al.*, "Formation and manipulation of ferrofluid droplets with magnetic fields in a microdevice: a numerical parametric study," *Soft Matter*, vol. 16, no. 41, pp. 9506–9518, Oct. 2020, https://doi.org/10.1039/D0SM01426E.

[5] N. Ali, J. A. Teixeira, and A. Addali, "A Review on Nanofluids: Fabrication, Stability, and Thermophysical Properties," *Journal of Nanomaterials*, vol. 2018, no. 1, 2018, Art. no. 6978130, https://doi.org/10.1155/2018/6978130.

[6] S. M. Sohel Murshed and C. A. Nieto de Castro, "A critical review of traditional and emerging techniques and fluids for electronics cooling," *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 821–833, Oct. 2017, https://doi.org/10.1016/j.rser.2017.04.112.

[7] A. Yadav, H. Kumar, R. Sharma, and R. Kumari, "Synthesis, processing, and applications of 2D (nano)materials: A sustainable approach," *Surfaces and Interfaces*, vol. 39, Jul. 2023, Art. no. 102925, https://doi.org/10.1016/j.surfin.2023.102925.

[8] K. Boukerma and M. Kadja, "Convective Heat Transfer of Al2O3 and CuO Nanofluids Using Various Mixtures of Water-Ethylene Glycol as Base Fluids," *Engineering, Technology & Applied Science Research*, vol. 7, no. 2, pp. 1496–1503, Apr. 2017, https://doi.org/10.48084/etasr.1051.

[9] N. A. C. Sidik, H. A. Mohammed, O. A. Alawi, and S. Samion, "A review on preparation methods and challenges of nanofluids," *International Communications in Heat and Mass Transfer*, vol. 54, pp. 115–125, May 2014, https://doi.org/10.1016/j.icheatmasstransfer.2014.03.002.

[10] F. Fievet *et al.*, "The polyol process: a unique method for easy access to metal nanoparticles with tailored sizes, shapes and compositions," *Chemical Society Reviews*, vol. 47, no. 14, pp. 5187–5233, Jul. 2018, https://doi.org/10.1039/C7CS00777A.

[11] S. Shahidi, B. Moazzenchi, and M. Ghoranneviss, "A review-application of physical vapor deposition (PVD) and related methods in the textile industry," *The European Physical Journal Applied Physics*, vol. 71, no. 3, Sep. 2015, Art. no. 31302, https://doi.org/10.1051/epjap/2015140439.

[12] W. N. Septiadi, I. A. N. T. Trisnadewi, N. Putra, and I. Setyawan, "Synthesis of hybrid nanofluid with two-step method," *E3S Web of Conferences*, vol. 67, 2018, Art. no. 03057, https://doi.org/10.1051/e3sconf/20186703057.

[13] W. T. Urmi, A. S. Shafiqah, M. M. Rahman, K. Kadirgama, and M. A. Maleque, "Preparation Methods and Challenges of Hybrid Nanofluids: A Review," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 78, no. 2, pp. 56–66, 2021.

[14] J. Okello, W. Mutuku, and O. Oyem, "A Review of Nanofluids Synthesis, Factors Influencing Their Thermophysical Properties and Applications," *Journal of Engineering Research and Reports*, vol. 17, no. 4, Oct. 2020, Art. no. 61551, https://doi.org/10.9734/JERR/2020/v17i417192.

[15] H. B. Bacha, N. Ullah, A. Hamid, and N. A. Shah, "A comprehensive review on nanofluids: Synthesis, cutting-edge applications, and future prospects," *International Journal of Thermofluids*, vol. 22, May 2024, Art. no. 100595, https://doi.org/10.1016/j.ijft.2024.100595.

[16] N. Abbas, M. B. Awan, M. A. Badshah, U. Sajjad, and W. Raza, "Nanofluids for enhanced performance of building thermal energy systems," in *Advances in Nanofluid Heat Transfer*, H. M. Ali, Ed. New York, NY, USA: Elsevier, 2022, pp. 479–501.

[17] A. K. Patra, M. K. Nayak, and A. Misra, "Viscosity of nanofluids-A Review," *International Journal of Thermofluid Science and Technology*, vol. 7, no. 2, Jun. 2020, Art. no. 070202, https://doi.org/10.36963/IJTST.2020070202.

[18] K. Anamalai *et al.*, "Multi-objective optimization on the machining parameters for bio-inspired nanocoolant," *Journal of Thermal Analysis and Calorimetry*, vol. 135, no. 2, pp. 1533–1544, Jan. 2019, https://doi.org/10.1007/s10973-018-7693-x.

[19] D. Guerraiche, K. Guerraiche, Z. Driss, A. Chibani, S. Merouani, and C. Bougriou, "Heat Transfer Enhancement in a Receiver Tube of Solar Collector Using Various Materials and Nanofluids," *Engineering, Technology & Applied Science Research*, vol. 12, no. 5, pp. 9282–9294, Oct. 2022, https://doi.org/10.48084/etasr.5214.

[20] K. Ramachandran, D. Ramasamy, M. Samykano, L. Samylingam, F. Tarlochan, and G. Najafi, "Evaluation of Specific Heat Capacity and Density for Cellulose Nanocrystal-based Nanofluid," *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, vol. 51, no. 2, pp. 169–186, 2018.

[21] S. Varala, T. Satish, A. Kumari, and A. K. Singh, "Microfluidic devices," in *Handbook of Biomolecules*, C. Verma and D. K. Verma, Eds. New York, NY, USA: Elsevier, 2023, pp. 241–256.

[22] M. K. S. Verma, A. Majumder, and A. Ghatak, "Embedded Template-Assisted Fabrication of Complex Microchannels in PDMS and Design of a Microfluidic Adhesive," *Langmuir*, vol. 22, no. 24, pp. 10291–10295, Nov. 2006, https://doi.org/10.1021/la062516n.

[23] S. F. Shah, G. Hussain, and A. T. Jafry, "Flow Control in Passive 3D Paper-Based Microfluidic Pump by Variable Porosity," *Engineering Proceedings*, vol. 12, no. 1, 2021, Art. no. 3, https://doi.org/10.3390/engproc2021012003.

[24] L. Luo, Y. Fan, W. Zhang, X. Yuan, and N. Midoux, "Integration of constructal distributors to a mini crossflow heat exchanger and their assembly configuration optimization," *Chemical Engineering Science*, vol. 62, no. 13, pp. 3605–3619, Jul. 2007, https://doi.org/10.1016/j.ces.2007.02.058.

[25] S.-W. Kang and S.-C. Tseng, "Analysis of effectiveness and pressure drop in micro cross-flow heat exchanger," *Applied Thermal Engineering*, vol. 27, no. 5, pp. 877–885, Apr. 2007, https://doi.org/10.1016/j.applthermaleng.2006.09.002.

[26] X. Lu and A. G. A. Nnanna, "Experimental Study of Fluid Flow in Microchannel," in *International Mechanical Engineering Congress and*

Exposition, Boston, MA, USA, Nov. 2008, pp. 647–653, https://doi.org/10.1115/IMECE2008-67932.

[27] M. M. Sarafraz, V. Nikkhah, M. Nakhjavani, and A. Arya, "Thermal performance of a heat sink microchannel working with biologically produced silver-water nanofluid: Experimental assessment," *Experimental Thermal and Fluid Science*, vol. 91, pp. 509–519, Feb. 2018, https://doi.org/10.1016/j.expthermflusci.2017.11.007.

[28] R. Chein and J. Chuang, "Experimental microchannel heat sink performance studies using nanofluids," *International Journal of Thermal Sciences*, vol. 46, no. 1, pp. 57–66, Jan. 2007, https://doi.org/10.1016/j.ijthermalsci.2006.03.009.