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Demonstration of plausible application of gallium nano-suspension in microchannel solar thermal receiver: Experimental assessment of thermo-hydraulic performance of microchannel

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ABSTRACT

The present study experimentally investigates the potential application of a liquid metal enriched with aluminum oxide nanoparticles in a microchannel, which can have further applications in designing the next generation of solar thermal receivers equipped with microchannel fluid passages. The gallium nano-suspensions were prepared at mass fractions of 5%, 10% and 15% of aluminum oxide in gallium and were utilized in a copper-made rectangular microchannel liquid block at 200 °C. Effects of different operating parameters such as heater heat flux, mass fraction of nanoparticles and peristaltic flow rate on the overall heat transfer coefficient, value of the pressure drop and thermo-hydraulic performance index of the microchannel were experimentally investigated. Results showed that gallium nano-suspension offers a great potential for cooling the surface of the microchannel at high heat flux condition. The highest thermal performance index of 3.5 and 2.9 were achieved for the flow in laminar and turbulent regimes at mass fraction of 10%. Likewise, heat flux and peristaltic flow rate plausibly enhanced the heat transfer coefficient, however, for the mass concentration, the thermo-hydraulic performance was decreased at wt% = 15, due to the augmentation in the viscosity and agglomeration of aluminum oxide nanoparticles within the gallium, which was attributed to the increase in friction forces between layers of gallium.

1. Introduction

Solar thermal energy is by far one of the reliable energy resources, which can be utilized to supply the required thermal energy for the domestic and industrial sectors. Solar energy is available, free to use and unlimited. One potential technology to use the solar thermal energy for supplying the required heat for chemical processes. In fact, Concentrated Solar Thermal energy (CST) is an under-developing technology with wide applications in chemical and heat processes. It employs a heliostat field or bundle of reflectors to concentrate the sun beams in a point, line or region where solar thermal receiver is placed to use the thermal energy. Currently, with the use of this technology, a high temperature operation of up to 1000 °C can be maintained [1]. However, there is a mismatch between the energy demand and the current capacity of the CST. This is because, the current heat transfer fluids have reached their limitations due to their poor thermal conductivity and operating temperature. Thereby, much effort has been made to seek alternative working fluids which have plausible thermal conductivity and high-temperature tolerance. For example, in a research conducted by Bellos et al. [2], a parabolic trough collector was assessed energetically and exergetically for the operating temperature of 25 °C to ~1000 °C. Different working fluids including pressurized water, Therminol VP1, nitrate molten salt, sodium liquid, air, carbon dioxide and helium were thermodynamically assessed and it was concluded that the liquid sodium presents the global exergetic maximum efficiency ~47.8%, followed by helium, carbon dioxide and air to be 42.2%, ~42.1% and 40.1%, respectively.

In the field of solar power cycles and engines, Ahmadi et al. [3] analysed the working performance of the solar powered engine for electricity by the use of hydrogen as a working gas. Although the results were promising, hydrogen limited the performance of the system in terms of temperature. Koichi Hirata [4] investigated a Stirling engine operated with Helium, Air, and Nitrogen and assessed the performance of the system for these working fluid. Wu et al. [5] studied the optimal performance of a Stirling engine and showed that Stirling engine cycle may have different efficiencies due to the different characteristics and physical properties of working fluids (Air and Helium). Thus, thermo-physical properties of the working fluid are determining parameters to overall thermal performance of the system. Thereby, one potential solution is to seek new generation of coolants with advanced thermal

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performance. The conventional coolants cannot be used in CST systems as their operating temperature is limited and also they have poor thermal conductivity and heat transfer coefficient [6–9].

Nanofluids are advanced engineering fluids which has been introduced in Argonne national laboratory [10]. Nanofluid is a colloidal suspension of solid materials (with the mean size of 0–100 nm) in conventional coolants such as water or ethylene glycol. Nanofluids have different applications in medical [11,12,51,52] and non-medical sectors. Nanofluids are known to enhance the thermo-hydraulic performance of the systems due to the enhancement in thermo-physical properties of base fluid such as thermal conductivity [13–15]. Since then, much effort has been made to assess the nanofluid for different applications including solar thermal energy. For example, a set of experiments were carried out to prepare sand-propylene glycol-water and measure the thermo-physical properties' measurement. The results showed a thermal conductivity enhancement of 16.3% and viscosity reduction of 47% for vol% = 2 of Sand-Propylene Glycol (PG)-water nanofluid at 28 °C. Despite the reasonable thermal performance, the introduced working fluid can only be used at temperatures less than the boiling point of PG [16] in order to maintain its stability and robustness.

The thermal conductivity and the transmissivity of silica aqueous nanofluid with mass fraction of 1%, 3% and 5% were tested in the experiments conducted by Yan et al. [17]. The temperature variations and velocity distributions of working fluid including water and nanofluid were calculated via numerical simulation to assess the thermal performance of silica nanofluid flow inside the collector tube. The results showed that the heat-transfer properties of SiO_2/water nanofluid were higher than that of water and increased with the mass fraction. The results also indicated that with the longer operation of nanofluid, agglomeration of nanoparticles will lead to the decrease in the heat transfer coefficient. Therefore, the proposed nanofluid was unable to be used under a continuous operation. Importantly, as the nanoparticles were dispersed in water, the operating temperature was limited to 100 °C, thereby it cannot be used for mid and/or high temperature applications. There are more studies in the literature in which despite the plausible heat transfer of nanofluid, they cannot be used in solar thermal systems due to the limitation in operating temperature of the base fluid [18,19]. Therefore, state of the art researches have been directed towards the new generation of base fluid such as molten salt which can tolerate continuous high-temperature operation. For example, molten salt has been used in Spain, for the CST plants of Termosol 1 and 2 (solar trough technology) for the operation of 9 h and in Gemasolar plant for the operation of 15 h. The molten salt tolerated the maximum temperature of 565 °C in the plants with power tower technology [20–22]. The molten salt was a mixture of sodium and potassium nitrate (60:40 by weight) known as Solar Salt, with a melting point of 238 °C [23]. This mixture was used instead the eutectic one ($NaNO_3$:KNO_3 50:50 by weight) to reduce the material costs [24].

Generally speaking, the aforementioned studies are now a driver for further research on molten salts to increase their operating conditions. Despite the fact the molten salt may offer better heat transfer properties, longer operation, lower cost and high-temperature tolerance, they suffer from following disadvantages:

- Significant corrosion and erosion due to the chemical reaction between molten salt and piping medium,
- Decomposition of molten salt at high-temperature condition [25],
- Huge solidification and low-freezing point in molten salts [26],
- Massive scale formation and friction factor leading to huge pressure drop.

Thereby, there is a need for further seeking of alternative heat transfer fluids to address the above issues. One potential option is to use liquid metals which not only have plausible heat transfer characteristics, but also they tolerate high-temperature conditions while presenting a very low vapour pressure and corrosion in comparison with molten salt (for a similar condition in a ceramic-made piping system e.g. alumina) [27].

In the present work, gallium has been selected as a potential heat transfer fluid to be introduced in solar thermal applications. The melting temperature of gallium is close to ambient temperature and this material presents a very low corrosion and vapour pressure.

Heat transfer fluid is not the only factor influencing the thermal performance of a thermal system. The heat exchanging medium is another matter of discussion, which needs to be taken in to the consideration. Microchannel heat exchangers are relatively new devices enabling one to transfer a large amount of heat using a small space with the help of high surface area exposed to the convective and/or nucleate heat transfer mechanisms. For the first time, Tuckerman and Pease [28] introduced a microchannel heat sink for cooling process of a processor, in which microchannel offered higher surface area for the heat transfer. They demonstrated that higher thermal performance in comparison with conventional processor coolers at the cost of pressure drop can be achieved, if a microchannel is used for the cooling process. The coolant was deionized water. Since Choi et al. [10] introduced the application of nanofluid in cooling systems, especial attention has been paid to the nanofluid flowing inside a microchannel heat sink. For example, Choi et al. [29] conducted a numerical study to investigate the cooling performance of a microchannel heat sink with nanofluids. Using a theoretical model of thermal conductivity of nanofluids that accounts for the fundamental role of Brownian motion, they showed that temperature contours and thermal resistance of a microchannel heat sink with nanofluids such as 6 nm copper/water and 2 nm diamond/water is decreased and the cooling performance of a microchannel heat sink with water-based nanofluids containing diamond (1 vol%, 2 nm) at the fixed pumping power of 2.25 W is enhanced by about 10% compared with that of a microchannel heat sink with water. However, in comparison with the penalty for pumping power, the enhancement was not plausible.

Later, performance of microchannel heat sink (MCHS) using nanofluids was investigated by Chein et al. [30]. They performed a theoretical analysis, followed by an experimental investigation to demonstrate that more energy and lower wall temperature can be obtained under the assumption that heat transfer is enhanced by the presence of nanoparticles. Experiments were then performed to verify the theoretical predictions. CuO/water was used at volume fractions of 0.2 to 0.4%. It was found that nanofluid-cooled heat sink can absorb more energy than water-cooled one when the flow rate was low. For high flow rates, the heat transfer was dominated by the volume flow rate and nanoparticles did not contribute to the extra heat absorption. The measured wall temperature variations agreed with the theoretical predictions for low flow rate. For high flow rate, the measured MCHS wall temperatures did not completely agree with the theoretical prediction due to the particle agglomeration and deposition. Therefore, they demonstrated that water is not a plausible coolant for the particulate system as it cannot retain the stability of coolant within the microchannel. Xie et al. [31,32] performed a numerical study to investigate the thermal performance of a rectangular mini-channel heat sink under a constant heat flux. They showed that the effect of dimension of channels, wall and bottom thicknesses of channel played a critical role on pressure drop and also the thermal performance. However, concentration changes in nanofluids were considered in the simulations. They also did not report any penalty or rise in pressure drop and friction factor. Ijam et al. [33] conducted a comparative investigation on thermal performance of a microchannel working with silicon/water and titanium/water nanofluids. They found out that silicon/water nanofluids presented a higher thermal conductivity, but titanium–water nanofluid could provide a more improvement on heat flux at 12.7%. Chai et al. [34–36] investigated the potential effect of the structure of design on of microchannel heat sinks and showed that an increase in heat interchanging area and redeveloping of thermal boundary layers were interacted on