CONVECTIVE HEAT TRANSFER OF MONO AND HYBRID NANOFLUID IN POROUS MICRO-CHANNEL: EXPERIMENTAL AND NUMERICAL APPROACH

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Introduction

Thermal energy storage (TES) systems are used to store or release thermal energy temporarily for later usage. The main purpose for the use of TES materials are due to fluctuating energy supply and demands along with varying production costs.

Ramachandran et al [1] conducted a study on the thermal performance of the following hybrid fluid combinations: 25% - 75%, 50% - 50% and 75% - 25% aluminum oxide / copper oxide nanoparticles respectively, with 0.1% volume concentration. The use of hybrid nanofluids will provide an enhancement in the heat transfer coefficient and the Nusselt number for a lower Reynolds number. Hybrid nanofluid is prepared by mixing the nanocomposite powder with deionized water. The hybrid nanofluid with 25% aluminum oxide and 75% copper oxide combination had a thermal resistance that was 44.25% lower than that of deionized water. A reduction in temperature was observed for the hybrid fluid containing 75% copper oxide and 25% aluminum oxide nanoparticles. This is due to the additional mass of the hybrid fluid brought upon by the copper particles, and so a larger hybrid fluid mass will result in a greater temperature drop. Studies on different hybrid fluid combinations, volume concentrations and various nanoparticles are often performed to obtain optimal thermophysical characteristics.

Suresh et al [2] conducted research on the Nusselt number and friction factors for alumina and copper oxide hybrid fluid with 0.1% volume concentration for flows in the laminar regime. The reason for the widespread use of alumina and copper oxide nanoparticles is for the fluid's excellent thermal properties, stability and it is quite inexpensive. The lower than average thermal conductivity of the aluminum oxide nanoparticles in comparison to most metallic particles is offset by the incorporation of the copper oxide fluid. The excellent physical stability and chemical inertness are properties of the former nanoparticles mentioned above. Thermal conductivity is dependent on the size, shape and material of the nanoparticles. Nusselt number enhancements are observed despite the volume concentrations at a very low 0.1%. The thermal conductivity increase of the hybrid fluid has a small effect on improvement of the heat transfer coefficient. It is possible that the random particle motion otherwise known as Brownian motion has significantly increased both the fluid's viscosity and thermal conductivity near the centerline. A flat velocity profile is a result of the increase in the hybrid fluid's viscosity which has led to a decrease in the difference between the average tube wall and bulk mean temperature. This reduction in the temperature difference in conjunction with the thermal conductivity improvement provided by the copper oxide nanoparticles has improved the overall heat transfer coefficient of the fluid. A significantly larger heat transfer coefficient and Nusselt number is observed when utilizing the hybrid fluid of both aluminum and copper oxide particles in comparison to aluminum oxide nanofluid. The hybrid nanofluid demonstrated a lower thermal resistance to convective heat transfer than that of alumina/water nanofluid. The increased viscosity is a characteristic of the hybrid fluids due to the nanoparticles forming clusters; as a result these fluids demonstrate a higher friction factor than that of deionized water. Therefore, hybrid fluids will also require a large pumping power than pure water. Hameed et al. [3] performed a comparative study on both the heat transfer and friction characteristics for Alumina-copper and Alumina-CNT hybrid nanofluids in laminar flow regime. When considering the convective heat transfer coefficient in a forced convection, there is a large dependence on the fluid velocity and its thermophysical properties. Thus, it is crucial to select a nanofluid that offers an overall optimal set of property values. Therefore, the purpose of the research conducted by Hameed et al. is to add onto the prior research conducted on various nanofluids and its heat transfer effectiveness, with hopes of determining the most effective hybrid fluid. The heat transfer enhancement as well as the Nusselt number for the Alumina-CNT hybrid fluid was significantly greater than that of Alumina-Cu hybrid fluid and Alumina nanofluid. The Alumina hybrid fluids with copper and carbon nanotubes had higher pressure drops than that of Alumina nanofluids. The Alumina-CNT hybrid fluid demonstrated the largest friction factor enhancement out of the tested hybrid fluids, and so its requires the most pumping power out of the fluids.

Experimental description

An experimental apparatus was developed to analyze the effect of pore density on the heat transfer characteristics within micro-channel porous media operating as heat sinks subjected to a forced flow. The test section consists of a porous micro-channel fluid chambers where the flow enters, a porous chamber containing the porous material, and a fluid chamber to allow the fluid to exit. The chamber is sealed to prevent any water leakage. An aluminum metal block was located below the porous material and a thermo paste material was inserted at the connecting point to allow good heat conduction. Thermocouples were inserted 1mm below this interface. The experimental setup used in the data collection process is similar to the one previously used by Bayomy et al. [4], however, the present apparatus includes variations in the geometric properties of the foam samples. These foam samples consisted of 6061-T6 aluminum manufactured by ERG Aerospace. The pore densities used was 40 PPI. The working fluid used within the system was nanofluid with 0.1% concentration of Al_2O_3.This fluid was recirculated through the apparatus to form a closed loop system. The metal block containing the three porous channels was cut to match the dimensions of the heater included within the apparatus (37.5mm x 37.5 mm). This sizing is consistent with the dimensions of an "Intel Core i7" processor.

Figure 1 shows the overall experimental setup and the numerical model. The heater was controlled using a dial. This allowed the experimenters to vary the current passing through the heater. This current was used to adjust and control the heat flux entering the system. A voltmeter and ammeter were connected to the heater to allow for the determination of the actual heat flux entering the system. Ten T-type thermocouples were used in the construction of the apparatus. Eight of these thermocouples were used to read and record the temperature distribution across the surface of the heater. The remaining two were used to record the inlet and outlet temperatures of the fluid passing through the metal foam. These thermocouples sent the data to a data acquisition system for recording and analysis. The pressure drop across the porous material was measured using a manometer connected across the test section. Lastly, a rotameter style flowmeter was placed in-line with the fluid flow to send volumetric flow rate readings to the data acquisition system.

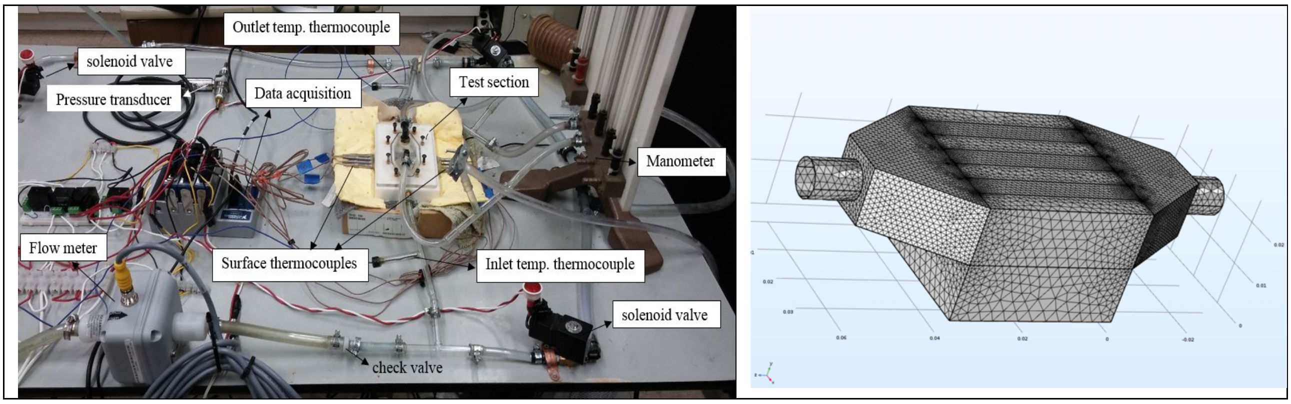

Figure 1. Experimental Setup and finite element model.

Finite Element Modelling and Boundary Conditions

The finite element modeling assumptions are taken into consideration, the Brinkman- Forchheimer equation and energy equation which describe the fluid flow and heat transfer inside the porous micro channel are solved using the following formulation:

$$\frac{\rho_f}{\varepsilon}\left(\frac{\partial U}{\partial t}+(U\cdot\nabla)\frac{U}{\varepsilon}\right)=\nabla.\left(-pI+\frac{\mu_f}{\varepsilon}(\nabla U+(\nabla U)^T)\right)-\left(\frac{\mu_f}{K}+\beta_f|U|\right)U+F$$

$$\nabla\cdot(\rho_f U)=0$$

$$(\rho c_p)_{eff}\cdot\frac{\partial T}{\partial t}+(\rho c_p)_f\,U\cdot\nabla T=\nabla.\left(k_{eff}.\nabla T\right)$$

where ρ_f represents the fluid density, c_p represents the fluid specific heat, ε represents the porosity of the aluminum metal foam, p represents the pressure, U represents the velocity field vector, β_f represents the Forchheimer coefficient, F represents the body force, T represents the temperature, μ_f represents the water dynamic viscosity, K represents the permeability of the aluminum foam and k_{eff} represents the effective thermal conductivity of the aluminum metal foam when filled with fluid. An accurate representation of the structural parameters of the metal foam is important for the estimation of effective thermal conductivity. For the fluid flow at the entrance of the porous channel and at the exit is solved using the Navier Stokes equation combined with the energy equation. For more details refer to reference [4].

Results and Discussions

Different model scenario will be presented in this paper. The fluid used in our experimental section consists of water mixed with Al_2O_3 nanoparticles. The concentration of these nanoparticles was 0.1%. The forced convection is applied to the three porous micro-channels model as shown in Figure 1. The porosity is 0.91 and a permeability of 40 PPI is used. The experimental results are compared with the numerical data to show the accuracy of the numerical model. The second segment of this paper is to repeat the experiment by using a hybrid mixture of water-Al_2O_3 and Cu. The aim is to examine the effect of thermal conductivities improvement on the heat transfer enhancement. The model will be solved numerically and a comparison with the mono nanofluid will be conducted.

Heat transfer enhancement using mono nanofluid with 0.1% of Al_2O_3

The experiment was conducted for four different flow rates of mono nanofluid of 0.23 US gallon per minute (USGPM), 0.18 USGPM, 0.15 USGPM and 0.1 USGPM respectively. The heat flux applied at the bottom of the plate was the other variable investigated in this experiment. It consists of three different heat fluxes of around 12 W/cm^2, around 7 W/cm^2 and finally around 5W/cm^2.

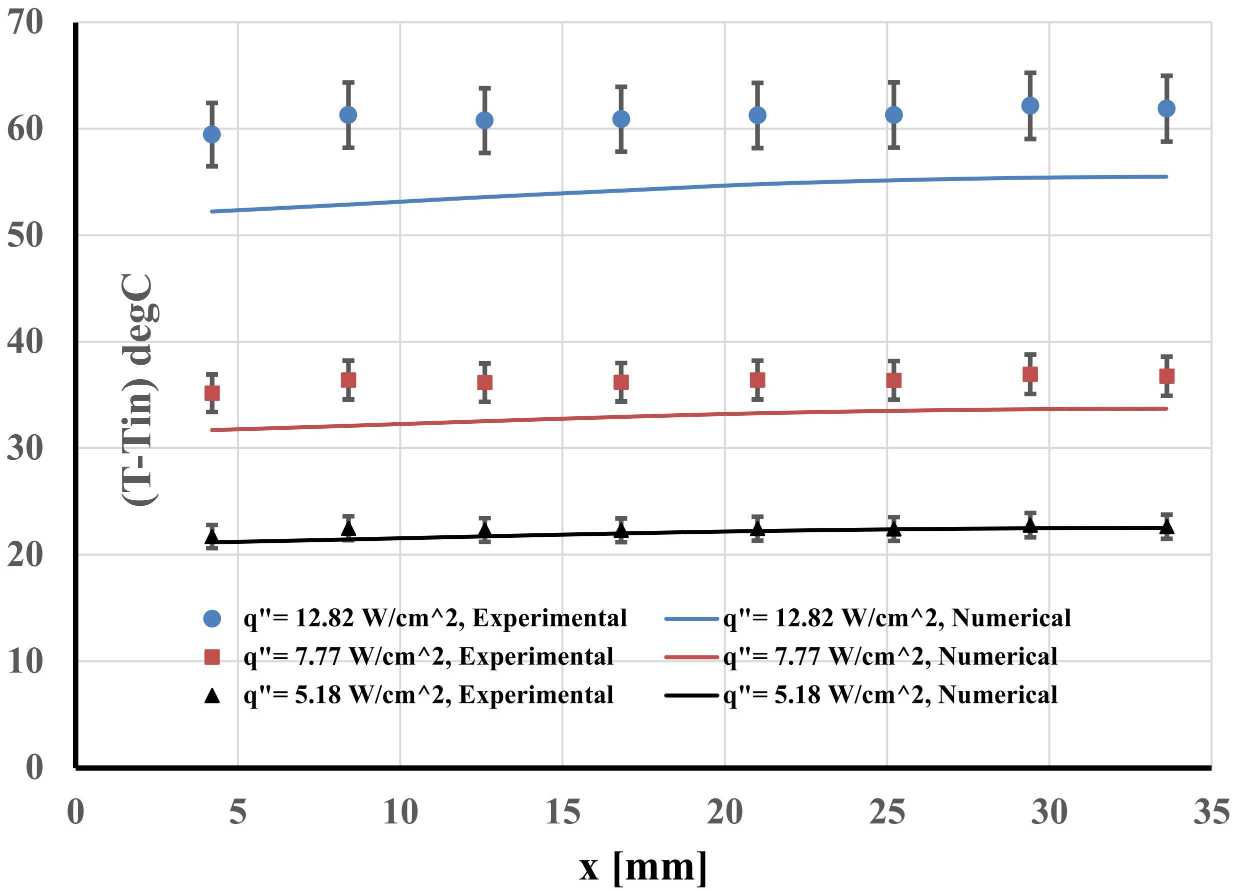

Figure 2. Temperature variation 1 mm below the microchannel (flow rate = 0.23 USGPM)

Figure 2 present the temperature variation 1mm below the three-channel flow when the flow rate is set at 0.23 USGM. As shown the trend between the experiment and the numerical model is accurate and the difference between the experimental and numerical results is due to many reasons. Amongst them, the accuracy of the thermocouples, the accuracy of the flow rate measurement and the accuracy of the heat flux reading. For more details about the uncertainty analysis the reader should refer to reference [4]. Here T_{in} is the inlet temperature which varied between each run.

Heat transfer enhancement using hybrid fluid with different concentration of Al_2O_3 and Cu

While preparing the experiment to be conducted using hybrid nanofluid, the performance of the hybrid fluid against mono nanofluid is investigated numerically using the finite element technique. Different flow rate of 0.1 USGM, 0.15 USGM, 0.18 USGPM and finally 0.23 USGPM were implemented. Two types of fluid are considered in this study. The first is a mono nanofluid of 0.1% Al_2O_3 with water and the second is 0.1% of a mixture of Al_2O_3 and Cu with water (i.e. hybrid nanofluid). A comparison between the two types of fluid confirmed that the hybrid fluid has a heat transfer enhancement exceeding the mono nanofluid by an average of 1%. This performance of hybrid fluid varies nonlinearly with the flow rate. Figure 3 shows the ratio of heat enhancement of hybrid fluid over the mono nanfluid for a constant heat flux of 5 W/cm^2 at different flow rate.

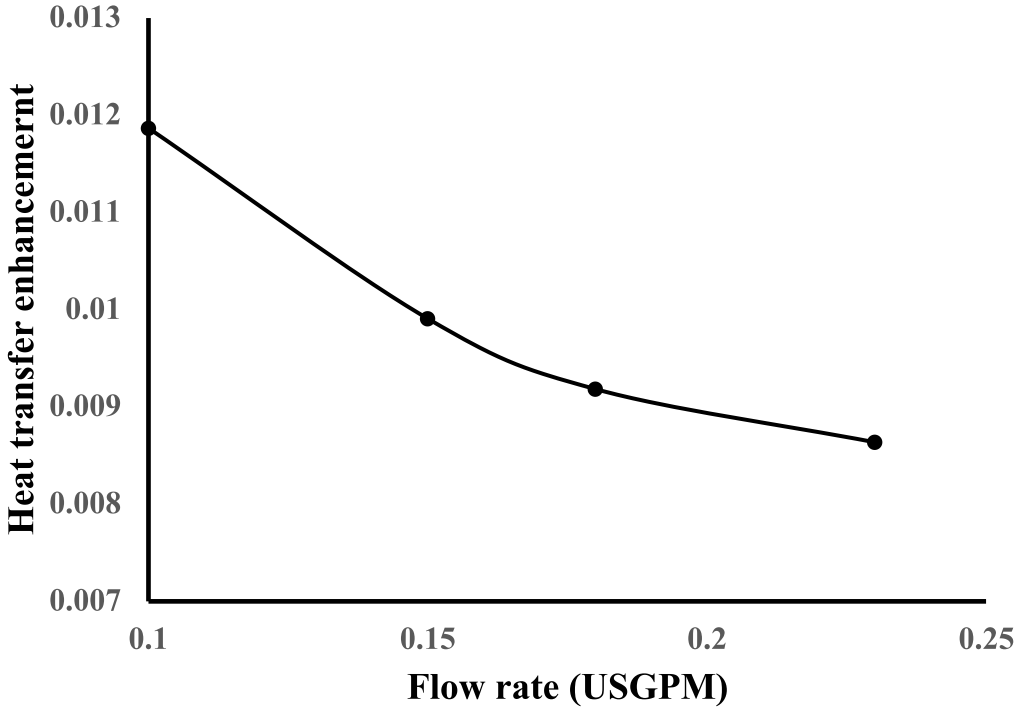

Figure 3. Heat transfer enhancement of hybrid fluid over mono nanofluid as function of the flow rate

Conclusions

We have demonstrated the usefulness in using hybrid fluid instead of mono nanofluid for heat enhancement. The results were shown for four different flow rates and the computation was conducted for different composition of mono nanofluid of water and Al_2O_3 nanoparticles. It appears that the usage of hybrid nanofluid is more appropriate for heat transfer enhancement than using mono nanofluid in porous media

Acknowledgements

The authors acknowledge the full support of National Science Research Council, Canada and Ryerson University for funding this project.

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