HYBRID NANOFLUIDS HEAT TRANSFER IN METAL FOAM AND COMPARISON TO ORDINARY NANOFLUIDS

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ABSTRACT

Nanofluids (NFs) are suspensions of metal or metal oxide nano particles in some common fluids (e.g. water, oil, coolants, etc.) The thermal advantages of NFs are that they provide a) higher thermal conductivity over base fluids and b) an increase in the convective heat transfer coefficient. These two advantages lead to better convective heat transfer when using nanofluids in engineering applications. Hybrid nanofluids (HNF) are the new generation of ordinary NFs. A HNF is a fluid that contains two or more kinds of chemically-distinct nanoparticles dispersed in a base liquid. HNFs are supposed to be more effective heat transfer fluids than NFs, as they present higher thermal conductivity, low viscosity and synergistic effects among nanoparticles. These effects are caused by different-size nanoparticles forming ordered arrangements around liquid molecules and acting as bridges among little aggregations of smaller nanoparticles. The literature has a considerable number of disagreements with regard to the properties and performance of NFs and HNFs as heat transfer fluids. This paper is part of a series of systematic studies to address this issue. Open-cell metal foams (MFs), e.g., aluminum, copper, nickel, has a web-like structure with open connected pores. The foams can have porosities exceeding 90%; and they are isotropic and exhibit uniform average geometrical properties. Thermal advantages of MFs stem from their high solid thermal conductivities, huge surface area density, and high permeability. Using NFs and HNFs as the cooling medium in MFs is likely to lead to enhanced convective heat transfer. In this paper, simulations of heat transfer of HNFs and NFs in aluminum foam are presented. The NFs and HNFs are made from aluminum oxide Al2O3 and TiO2 nanoparticles and suspended in deionized water. The comparison between the performance of these fluids is made at the same solid particle volume concentration and hydraulic and thermal conditions. The simulation domain is a circular pipe having an internal diameter 5.25 cm and a length 16.51 cm and filled with aluminum foam with 20 pores per inch and a porosity of 95%. The pipe is subjected to constant heat flux of 15518 W/m2. At the inlet, the fluid's temperature was constant at 298 °K, and the entrance velocity ranged between 0.029 and 0.038 m/s (uniform profile). All data is in the laminar flow regime. The single-phase model for each NF and HNF is utilized. All simulations are conducted utilizing ANSYS Fluent. The mesh-independent results show that the heat transfer performance of HNFs is found to be superior to that of NFs.

INTRODUCTION

Nanofluids are typically liquids with solid nanoparticles of metals or metal oxides suspended in them. The nanoparticles must be less than 100 nm in size. Based fluids are usually typical common coolants such as water and ethylene glycol. Other base fluids include phase-change materials such as paraffin, and refrigerants. Metal nanoparticles have been often made from copper, silver, and gold. Metal-oxide nanoparticles have been usually alumina, titania, and iron oxide. Graphene nanosheets and carbon nanotubes have been used to make nanofluids with higher conductivity. Sedimentation and stability have been some of issues with nanofluids. Surfactants or dispersants are often used to keep the nanoparticles suspended and dispersed in base fluids. Nanofluids were proposed as coolants in Argonne National Laboratory (USA) in 1995[1]. Scientific research on nanofluids has been exponentially rising ever sense. increase ever since.

The common based fluids have poor thermal conductivities, and adding nanoparticles increased their conductivity. This enhanced conductivity improves thermal performance. Moreover, nanoparticles themselves enhance the convective heat transfer coefficient.[2] However, adding nanoparticles increases viscosity, which leads to higher pressure drop. Nonetheless, nanofluids are viewed as the next generation coolants. There are some guidelines for choosing nanofluids to enhance heat transfer.[3]

A hybrid nanofluid is an advanced nanofluid that contains two or more kinds of chemically-distinct nanoparticles dispersed in a base liquid. HNFs are a recent evolution of nanotechnology. HNFs are more effective heat transfer fluids than ordinary nanofluids (mono-nanoparticle fluids), as they present higher thermal conductivity, low viscosity and synergistic effects among nanoparticles. These effects are caused by different-size nanoparticles forming ordered arrangements around liquid molecules and acting as bridges among little aggregations of smaller nanoparticles. These peculiar HNFs phenomena lead to effective heat transfer networks. Also, by hybridizing the appropriate combination of nanoparticles, one can get the desired heat transfer effect even at low particle concentrations.[4] While ordinary nanofluids have been around since 1995, HNFs have started receiving increased attention around 2015. Currently there is a lack of understanding of transport phenomena of HNFs.

The literature shows that the vast majority of the published work on HNFs is concerned with determining thermophysical properties, and has as primary focus flow in clear channels. The research on HNFs began to emerge about 10 years ago, and is still limited both experimentally and numerically.[5] The vast majority of recent papers is focused on thermophysical properties of HNFs,[6-8] and have not considered metal foam as core. Other investigations specifically focused on the thermal conductivity of HNFs due to its vital role in heat transfer enhancement, and on viscosity due to its role in pressure drop.[9-11] Asadi et al.[12] experimentally investigated the effects of temperature and solid volume fraction on the dynamic viscosity and thermal conductivity of Mg(OH)2/MWCNT-engine oil HNF. Correlations for the two properties were proposed. Similarly, Sadi et al.[13] provided correlations for the dynamic viscosity and thermal conductivity of Al2O3-MWCNT/thermal oil HNFs. Charab et al.[14] proposed a model for the

thermal conductivity of Al2O3-TiO2 HNFs with different particle ratios. Hamid et al.[15] experimentally showed that the thermal conductivity of TiO2-SiO2 HNFs increased by up to 16% compared to base fluid.

The literature on convection heat transfer characteristics of HNFs is relatively small, and it involves HNFs flow through clear conduits (without metal foam). Available studies clearly indicate that HNFs yield high rates of heat transfer. Bhattad et al.[16] recorded a maximum enhancement of 16.9% for the convective heat transfer coefficient with Al2O3-TiO2 HNF, along with 0.013% increase in pump work for a plate heat exchanger. Similarly, enhancements were reported when using HNFs in other kinds of heat exchangers.[17-19]

Metal foams, e.g., aluminum, copper, nickel, has a web-like structure with open connected pores, Fig. 1. The foam can have porosities exceeding 90%; and they are isotropic and exhibit uniform average geometrical properties.[20,21] Thermal advantages of MFs stem from their high solid thermal conductivities, huge surface area density (up to 10,000 m^2/m^3),[22,23] and high permeability in the order of 10^{-8} m^2,[24,25] yielding a relatively small impact on pressure drop. Additionally, the nature of foams' internal structure causes vigorous mixing which augments convection. MFs have been sought for compact heat exchangers,[26,27] thermal management of fuel cells,[28] and of high-power batteries: combining aluminum foam with phase change materials caused a 50% temperature drop and provided uniform temperature of Li-ion batteries.[29] In recent years, investigators have continued studying heat transfer in MFs for critical energy applications, e.g. solar energy,[30,31], Li-ion batteries,[32,33] and fuel cells.[34,35] Recent research work on metal-foam heat exchangers is available.[36,37]

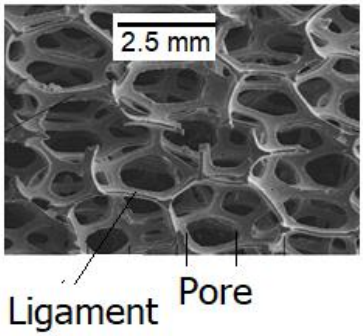

Figure 1. Morphology of open-cell metal foam.

Thermal management of high-power systems require new capable thermal technologies. Combining metal foam with nanofluids may offer an advance cooling arrangement. Metal foam provides huge accessible surface area per unit volume, and its internal web-like structure causes strong mixing, which improves convection heat transfer. The nanofluids would provide highly-conductive working fluids that would carry more heat. This paper is part of a series of investigations geared to further establish the performance of the hybrid nanofluids.

SIMULATIONS

Adopted model of nanofluids

There are two theoretical models of nanofluids: the single-phase model (SPM) and the two-phase model (TPM). The SPM treats nanoparticles and base fluid as a single phase, and assumes that local thermal equilibrium holds between the two constituents. These assumptions are justified due to small size of nanoparticles. Governing equations that are used for conventional fluids can be used for single-phase nanofluids. Thermophysical properties of nanofluids need to be determined and inserted in these governing equations. Obviously, the SPM produces results that are strongly dependent on the thermophysical properties of nanofluids. Many researchers reported that heat transfer in nanofluids can be modelled using the SPM. [38,39]

The two-phase model (TPM) on the other hand treats nanoparticles and the base fluid as two different phases. Two sets of governing equations are needed- one set for each phase. The TPM is preferred by some researchers because there is concentration variation of nanoparticles in the flow. There is an on-going debate as to which of the two models provides more accurate fluid mechanics and heat transfer results. Recently, Wen et al.[40] presented a numerical study of the heat transfer and flow behavior of ZnO ethylene glycol (EG)/water nanofluid inside two multiport mini channels. The SPM gave better predictions for both Nusselt number and friction factor, while the TPM model severely overestimated the Nusselt number, but showed a reasonable friction factor prediction. The SPM is used in the current study for simplicity and due to the small size of nanoparticles.

Properties of nanofluids

Simulations and analysis of nanofluids require determination of their relevant properties. Properties of a nanofluid depend on the properties of base fluid and nanoparticles dispersed in it. The properties of nanofluids also strongly depend on concentration and temperature. For flow and heat transfer investigations, key thermophysical properties are density, viscosity, specific heat, and thermal conductivity.

The volume fraction ϕ , of nanofluids is the solid nanoparticles volume ϕ_s divided by the mixture volume ϕ_{tot} prior to mixing:

$$\phi = \phi_s/\phi_{tot} \tag{1}$$

In the current study, the nanofluids were made from aluminum oxide Al2O3 and TiO2 suspensions in deionized (DI) water. The hybrid nanofluid was made by suspending Al2O3 and TiO2 in DI water with 50:50 of the two kinds of nanoparticles. In all cases, the volume fraction was 1.5%. The thermophysical properties of nanoparticles are given in Table 1. These properties were used to compute the properties of the resulting nanofluids and the hybrid nanofluid.

Table 1. Properties Of Nanoparticles and Water as Used in This Study

Property	Al2O3	TiO2	Water
ρ (kg/m^3)	3900	4250	998.2
k(w/m.K)	42.34	8.4	0.6
C_p(J/kg.K)	880	692	4182
μ(kg/m.s)	NA	NA	0.001003

For the ordinary nanofluids, properties were calculated from the following correlations. The density from: [9,10]

$$\rho_{nf} = (1-\varphi)\rho_f + \varphi\rho_s \tag{2}$$

The specific heat from:[41,42]

$$(\rho Cp)_{nf} = (1-\varphi)(\rho Cp)_{bf} + \varphi(\rho Cp)_s \tag{3}$$

Viscosity from:[41]

$$\frac{\mu_{nf}}{\mu_f} = \frac{1}{(1-\varphi)^{2.5}} \tag{4}$$

Thermal conductivity from:[41,43]

$$\frac{k_{nf}}{k_f} = \left[\frac{k_s + 2k_f - 2\varphi(k_f - k_s)}{k_s + 2k_f + \varphi(k_f - k_s)}\right] \tag{5}$$

Here the subscripts s, f or bf, nf refer to solid nanoparticles, fluid or base fluid, and nanofluid, respectively. As for the hybrid nanofluids, properties were computed from the following correlation:

The density of HNF is given as:[44, 45]

$$\rho_{hnf} = (1-\varphi)\rho_{bf} + (0.5-\varphi)\rho_{Al2O3} + (0.5-\varphi)\rho_{TiO2} \tag{6}$$

The specific heat and viscosity are obtained from:[44-46]

$$C_{hnf} = \frac{(1-\varphi)\rho_{bf}C_{bf} + (0.5\times\varphi)\rho_{Al2O3}C_{Al2O3} + (0.5\times\varphi)\rho_{TiO2}C_{TiO2}}{\rho_{hnf}} \tag{7}$$

$$\frac{\mu_{hnf}}{\mu_{bf}} = \frac{1}{(1-\varphi_{TiO2})^{2.5}(1-\varphi_{Al2O3})^{2.5}} \tag{8}$$

The conductivity is calculated from:[45,46]

$$\frac{k_{hnf}}{k_{bf}} = \left[\frac{k_{TiO2} + 2k_{bf} - 2\varphi_{TiO2}(k_{bf} - k_{TiO2})}{k_{TiO2} + 2k_{bf} + \varphi_{TiO2}(k_{bf} - k_{TiO2})} \right] \tag{9}$$

where

$$\frac{k_{bf}}{k_f} = \left[\frac{k_{Al2O3} + 2k_{bf} - 2\varphi_{Al2O3}(k_{bf} - k_{Al2O3})}{k_{Al2O3} + 2k_{bf} + \varphi_{Al2O3}(k_{bf} - k_{Al2O3})} \right] \text{[24,25]} \tag{10}$$

All obtained properties for HNF are listed in Table 2.

Table 2. Hybrid Nanofluid's Properties for 1.5% Concentration

Property	Al2O3/TiO2Water
ρ (kg/m^3)	1044.35
k(w/m.K)	0.65
C_p(J/kg.K)	3989.9
μ(kg/m.s)	0.001089

Details of the simulated problem

The convective heat transfer system that was simulated is shown schematically in Fig. 2. An aluminum pipe with constant cross section having an internal dimeter of 5.25 cm and an external diameter of 6.05 cm, and filled with open-cell aluminum foam having a porosity of 95% and a linear pore density of 20 pores per inch. The length of the pipe is 15.24 cm in the flow direction. There is a constant heat flux applied on the external surface of the pipe. A coolant (water or nanofluid) enters the pipe from the left and flows to the right. The flow has a uniform velocity profile at the inlet. The outlet of the pipe is open to the atmosphere.

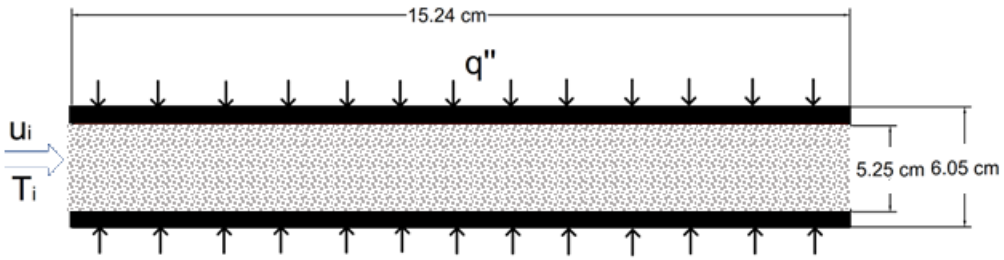

Figure 2. Schematic of the convection heat transfer problem.

The following boundary conditions were applied:

At the inlet, the fluid temperature Ti = 298 K, and the entrance velocity ui = 0.029 m/s (uniform profile at the inlet). On the external surface of the pipe a constant uniform heat flux q" = 15518 W/m^2 is applied.

Simulation details and mesh independence

All simulations were conducted utilizing ANSYS Fluent 2021 R1 on a local station AMD Ryzen 7 1st Gen - RYZEN 7 1700X Summit Ridge (Zen) 8-Core 3.4 GHz (3.8 GHz Turbo) with dual processors, 64 cores, and 32.0 GB RAM. All meshes consist of uniform square-shaped elements with near-wall higher density to capture any small temperature variations. Even though the maximum Reynolds number was Re = 2125, which makes this pipe flow laminar, a k-ε turbulent model was adopted in the simulation, based on recommendation by Fluent. Each run took approximately 25 minutes to converge.

A mesh independence check was conducted for various mesh densities. It is crucial to optimize the size of the cells and the density of the elements to get an accurate solution. The total temperature was calculated across the test section for different mesh densities. Once the average total temperature across the test section stops changing by more than 2%, as the element is refined, then the mesh used was deemed adequate. Based on the mesh independence study, the final mesh had a total of 588491 elements and 600710 nodes.

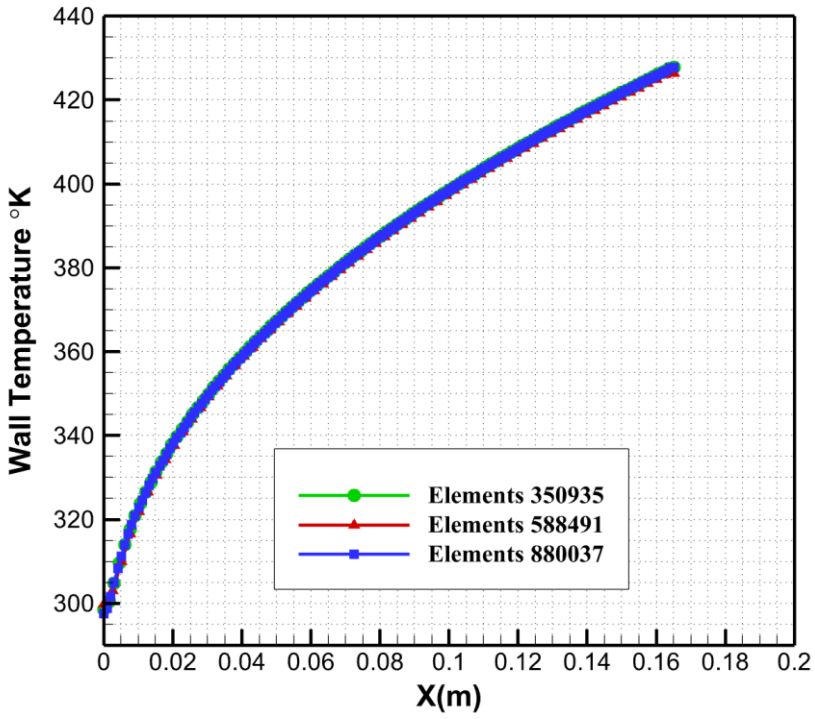

Figure 3. Mesh independence.

RESULTS

Figure 4 shows the variation of the local surface temperature in the flow direction for the two nanofluids and the hybrid nanofluid- all the same volume fraction of 1.55. The case for clear water is also included for reference. The following can be observed. The two nanofluids are seen to produce approximately the same wall temperatures along the pipe, which indicates similar cooling performance of the two fluids. For the two nanofluids, the wall temperature is significantly lower than that for water. The hybrid nanofluid is seen to produce a much lower wall temperature, which indicated a superior cooling performance of this advanced fluid compared to mono nanofluids. The gaps between the surface temperature for all fluids are seen to increase along the pipe.

Clearly, there is thermal development in all cases: the temperature starts to increase gradually with a changing slope, and at a certain location, the slope becomes constants indicating full development. For water full thermal development occurs at about seven cm from the inlet, while it occurs earlier for the nanofluids (at about 5 cm from the inlet). After full development, the average decrease in the wall temperature for the HNF is about 50% compare to the two nanofluids.

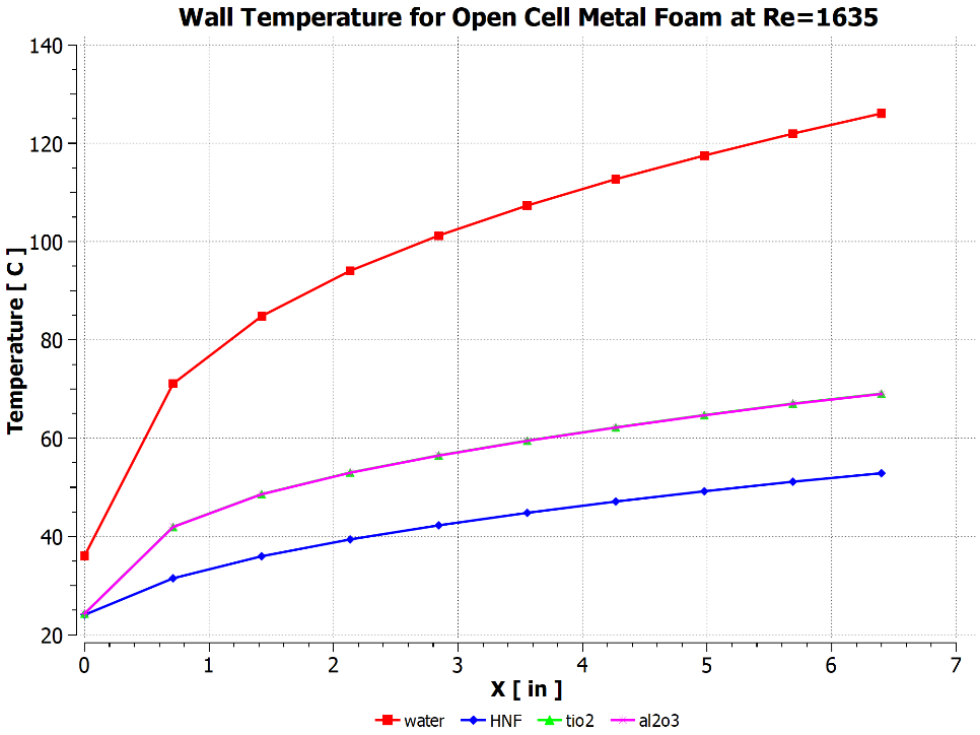

Figure 4. Surface temperature along flow direction for nanofluids and hybrid nanofluid.

CONCLUSION

Convective heat transfer simulations for two nanofluids and one hybrid nanofluid made from the same nanoparticles at the same volume concentration of 1.5%. The common case of a heated circular pipes having a constant surface heat flux was analyzed. The single-phase model was adopted for the nanofluids, and their properties were obtained from correlations in the literature. The wall temperature for the hybrid nanofluid was seen to be significantly lower than that obtained with each of the two nanofluids (20 ^{o}C lower). This lower temperature indicated better heat transfer performance of the hybrid nanofluid. The results are encouraging but further cases need to be investigated to further establish the superiority of hybrid nanofluids as coolants. More specifically, the effect of flow Reynolds number and the volume concentration need to be varied and their effects on heat transfer for these fluids needs to be pursued.

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