Performance Comparison of Nanofluids in Laminar Convective Flow Region Through a Channel

Md Insiat Islam Rabby, S. A. M. Shafwat Amin, Sazedur Rahman, Farzad Hossain, Mohammad Ahnaf Shahriar and A. K. M. Sadrul Islam

Abstract In this numerical study, the thermal performance of Al_2O_3–H_2O, CuO–H_2O, SiC–H_2O and TiO_2–H_2O nanofluids has been analyzed for laminar flow region of a channel which is fully developed. For this purpose, the figure of merit (FOM), power for pumping, Nusselt number enhancement ratio and heat transfer coefficient ratio of base fluid and nanofluids are calculated for constant Reynolds number and (1–5%) volume concentration of four nanofluids. The computational analysis and results show that the FOM is higher for Al_2O_3–water nanofluid compared to others at constant Reynolds number. On the other hand, the Nusselt number enhancement ratio is higher for CuO–water nanofluid compared to others, and Al_2O_3–water shows higher enhancement ratio of heat transfer coefficient compared to others, and this is happened because of the higher thermal and physical properties like thermal conductivity, density and viscosity of the Al_2O_3–water. And at constant heat transfer coefficient, the pumping power has been reduced for all the nanofluids compared to pure water, and Al_2O_3–water shows more reduction of pumping power compared to other nanofluids.

Keywords Figure of merit · Pumping power · Nusselt number enhancement ratio · Heat transfer enhancement ratio

1 Introduction

From the last few decades, the importance and research on nanotechnology are the most fundamental and effective topics of thermal engineering. At present to improve heat transfer efficiency and heat transfer rate, nanoparticles are used with base fluids. Beside this, the utilization of pumping power to get this enhancement is also less, and this is the most advantage thing to using nanoparticles in working fluids. Basically, by adding small amount of solid particles with the base or working fluid, the thermal conductivity of the fluid can be increased noticeably. And by using this concept,

M. I. I. Rabby (✉) · S. A. M. Shafwat Amin · S. Rahman · F. Hossain · M. A. Shahriar · A. K. M. Sadrul Islam
Military Institute of Science and Technology, Dhaka, Bangladesh
e-mail: insiatislam8@gmail.com

L. Li et al. (eds.), *Advances in Materials and Manufacturing Engineering*, Lecture Notes in Mechanical Engineering, https://doi.org/10.1007/978-981-15-1307-7_58

researchers have been made nanofluid which is the combination of base fluids (water, engine oil or ethylene glycol) and very small amount of solid particles at nanoscale size (1–100 nm). Al_2O_3, CuO, TiO_2, SiC, SiO_2, Fe_2O_3, MgO, etc. particles are used as nanoparticle to mix with base fluids. Different researchers carried out their investigation on nanofluids at heat transfer application. Xuan and Li 2003 [1] worked on Cu–water nanofluid through a 10-mm inward distance across tube for convective transfer of heat. The results from their investigation reveal that at turbulent, the friction factors for volume fraction 1 and 2% of nanofluids are showed similar value compared to pure water. Williams et al. 2008 [2] experimentally carried his study on the convective turbulent heat exchange of alumina–H_2O and zirconium–H_2O water nanofluids in a tube. They investigated that nanofluids provide enhancement of heat exchange and behavior of viscous pressure drop. Rea et al. [3] led an investigation on the convective warmth exchange and weight drop of alumina–H_2O and zirconium–H_2O nanofluids in a tube for laminar flow which width is 4.5 mm (inward). But from their discoveries, there is no deviation in convective heat exchange and weight drop of nanofluid has been found. Heris et al. [4] played out an exploratory investigation to decide the loss of pressure and transfer of heat qualities of Al_2O_3–H_2O and CuO–H_2O nanofluids through a triangular conduit under uniform heat flux at laminar flow area. Their outcomes demonstrated that, at similar/constant volume concentration and Reynolds number, utilizing CuO nanoparticle is less beneficial than Al_2O_3 nanoparticles. Yu et al. [5] worked with SiC–water nanofluid for turbulent flow and a comparison parameter the figure of the merit which is denoted by heat transfer enhancement and pumping power ratio were presented in their study. Their result showed that SiC–water nanofluid provided the value of FOM 0.8 and Al_2O_3–water nanofluid provided the value of FOM 0.6 which indicates that SiC–water nanofluid is more favorable in case of pumping power penalty. Yu and Dong [6] studied on convective thermal performance investigation of nanofluids (Al_2O_3–water and Al_2O_3–polyalphaolefin) for cooling applications, and their result reveals that in case of constant pumping power condition, the nanofluid's and the base fluid's overall effectiveness will not be changed significantly when both the hydrodynamic and thermal performances are considered. Sarkar [7] carried out his research work on performance analyses of the nanofluids Al_2O_3, TiO_2, CuO and Cu as cooling application for cooled gas cooler (shell-and-tube) in CO_2 refrigeration cycle which is transcritical. Their research shows that the effectiveness of nanofluid is preferable to use it as coolant in the gas cooler to develop and improve the performance of the cycle of CO_2 refrigeration. Monjur [8] investigated on energy savings of heat exchanger, and they showed that for constant heat transfer coefficient, Al_2O_3–water, CuO–water and TiO_2–water required less pumping power and volumetric flow rate compared to pure water. Ingole et al. [9] investigated on pumping power of car radiator by using Al_2O_3–water nanofluid, and they find that 2% volume concentration of Al_2O_3–water need 23.81% less pumping power compared to pure water.

The above maximum researches only show higher heat transfer rate by using nanofluids, but very few papers show the justification of required pumping power study to get the higher heat transfer rate and also comparison between nanofluids on the basis of required pumping power. So in the present work, the thermal performance of four nanofluids Al_2O_3–H_2O, CuO–H_2O, SiC–H_2O and TiO_2–H_2O has been studied, and the results are compared on the basis of pumping power requirement. Moreover, the figure of merit (FOM), Nusselt number enhancement ratio, heat transfer coefficient ratio and pumping power of base fluid along with nanofluids are calculated for constant Reynolds number and (1–5%) volume fraction. Basically, the overall performance of water-based nanofluids in the forced convective laminar regime is discussed in terms of three merits criteria. They are Nusselt number enhancement ratio, heat transfer enhancement ratio and figure of merit (FOM). The first two ones are usually used to compare different fluids of heat transfer, while other can be mainly used to evaluate nanofluid's overall energetic performance for operating condition in a real system. Meanwhile, a higher value of figure of merit represents more gain in the heat exchange enhancement compared to the pumping power increment.

2 Physical Geometry and Boundary Condition

Parallel plates with a steady heat flux on both walls are presented to examine the performance of all the nanofluids through the channel of Fig. 1 by employing numerical method using ANSYS fluent software. The distance between two horizontal plates is 4 mm, and length is 600 mm length. A constant uniform heat flux of 500 W/m^2 is applied on the wall boundary of the parallel plates, and fluid is permitted to flow with constant temperature of 303 K at the opening of the parallel plates with a presumption of no slip condition on the parallel plate's wall which are considered. All the heat exchange and fluid dynamic parameters are extricated after the thermal and hydrodynamic improvement of the fluid stream, and in this case, for taking all the

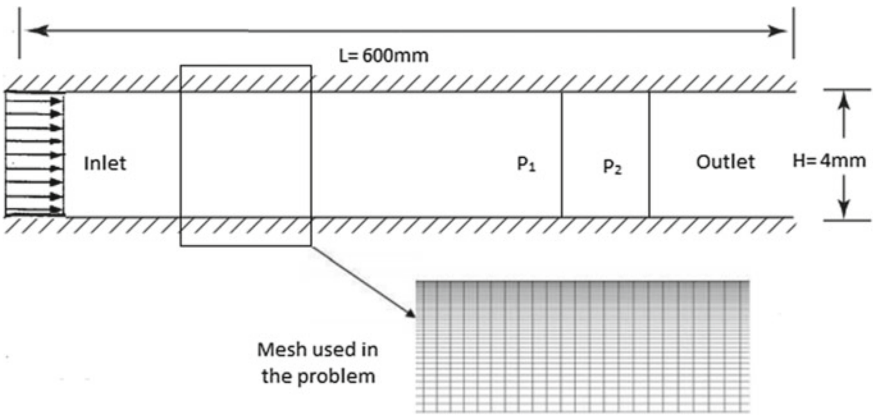

Fig. 1 Corresponding geometry of present work with mesh

measurements the standard entrance length is considered $x/D = 60$. For calculating the heat transfer enhancement and pressure loss, the temperatures are taken at line which is situated 590 mm from inlet, and pressures are taken at lines which are situated from 565 to 555 mm from the inlet.

3 Numerical and Computational Method

We use ANSYS (fluent) which is commercial computational fluid dynamics software for this numerical analysis. All the governing equations for momentum, mass, energy and laminar quantities have been solved by adopting a control volume technique. A simple algorithm has been used for velocity pressure coupling purpose, and a second-order upwind method has been used to solve energy and momentum equation. At inlet laminar inlet velocity and at the outlet boundary pressure, outlet is considered. Under relaxation factors, 0.4 for pressure, 0.76 for momentum, 1 for energy and 0.9 for density equation are considered for parallel plate. All the used nanoparticles with volume fractions (1, 2, 3, 4 and 5%) are mixed with water separately and tested with a wide range of Reynolds number 400–1100 and then results are compared with base fluid water.

4 Methodology

The governing equations for continuity, momentum and energy for forced convection under laminar steady-state flow conditions are represented as follows:

Continuity equation: In steady flow, the conversations of mass eq^{n}:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

Momentum equation: For laminar flow, the momentum equation:

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \mu\frac{\partial^2 u}{\partial y^2} \tag{2}$$

Energy equation:

$$(E_{in} - E_{out}) = k\frac{d^2T}{\partial x^2}\mathrm{d}x\mathrm{d}y + k\frac{d^2T}{\partial y^2}\mathrm{d}x\mathrm{d}y = k\left(\frac{d^2T}{\partial x^2} + \frac{d^2T}{\partial y^2}\right)\mathrm{d}x\mathrm{d}y \tag{3}$$

5 Thermal and Fluid Dynamics Properties

The Reynolds number for nanofluids:

$$Re = \frac{\rho_{nf} U_{av} D_h}{\mu_{nf}} \tag{4}$$

Average Nusselt number:

$$Nu = \frac{h_c D_h}{K_{nf}} \tag{5}$$

Rate of heat transfer

$$Q_{nf} = m_{nf} C_{P_{nf}} \Delta T \tag{6}$$

Average heat transfer coefficient h_c:

$$h_c = \frac{Q_{nf}}{A_w(\Delta T)} \tag{7}$$

Temperature difference:

$$\Delta T = \frac{(T_w - T_o) - (T_w - T_i),}{\ln\left(\frac{T_w - T_o}{T_w - T_i}\right)} \tag{8}$$

Pressure difference:

$$\Delta P = \frac{f L \rho U^2}{2 D_h} \tag{9}$$

Nusselt number enhancement ratio

$$= \frac{Nu_{nf}}{Nu_{bf}} \tag{10}$$

Overall heat transfer coefficient enhancement ratio

$$= \frac{h_{nf}}{h_{nf}} \tag{11}$$

The pumping power per unit length:

$$W = \frac{(\pi/4) D^2 U_{av} \Delta P}{L} \tag{12}$$

The figure of merit,

$$\text{FOM} = \left(\frac{h_{nf}}{h_{bf}}\right)\left(\frac{W_{bf}}{W_{nf}}\right) \tag{13}$$

6 Thermophysical Properties of Nanofluids

Dynamic viscosity: There are several equations for dynamic viscosity; among them, we use Pak and Cho [10] equation for TiO_2, Nguyen [11] equation for CuO, Maiga [12] equation for Al_2O_3 and Chein [13] equation for SiC. The equation can be expressed as:

For TiO_2–water nanofluid:

$$\mu_{nf} = \mu_{bf}(1.0683 + 4.70\emptyset + 167.7\emptyset^2) \tag{14}$$

For CuO–water nanofluid:

$$\mu_{nf} = \mu_{bf}(1.475 - 0.319\emptyset + 0.051\emptyset^2 + 0.009\emptyset^3 \tag{15}$$

For Al_2O_3–water nanofluid:

$$\mu_{nf} = \left(1 + 7.3\emptyset + 123\emptyset^2\right)\mu_f \tag{16}$$

For SiC–water nanofluid:

$$\mu_{nf} = \mu_{bf}\left[1 + 10.6\emptyset + (10.6\emptyset)^2\right] \tag{17}$$

Thermal conductivity: There are several thermal conductivity equations; among them, we use Pak and Cho [10] equation for TiO_2, CuO and Al_2O_3. For SiC, we use Maxwell [14] mode equation. The following formulas are:

For TiO_2–water nanofluid:

$$K_{nf} = (1.0084 + 2.1796\emptyset) \tag{18}$$

For Al_2O_3–water nanofluid:

$$K_{nf} = K_{bf}(1.0021 + 7.3349\emptyset) \tag{19}$$

For SiC–water and CuO–water:

$$K_{nf} = \frac{K_p + 2K_{bf} + 2\left(K_p - K_{bf}\right)\emptyset}{K_p + 2K_{bf} - \left(K_p - K_{bf}\right)\emptyset \times K_{bf}} \tag{20}$$

Density: (Xuan and Roetzel, 2000) [15] eq^n

$$\rho_{nf} = \rho_p \O + \rho_{bf}(1 - \O) \tag{21}$$

Specific Heat: Pak and Cho, 1998 [10] equation:

$$C_{nf} = (1 - \O)C_w + \O C_p \tag{22}$$

7 Code Validation Test

For channel flow, at uniform velocity and constant heat flux water was passed through it and a range of Reynolds number (400-1100) were considered for calculating Nusselt numbers to validate the present work with validated equation of Nusselt number for channel flow. At fully developed zone, obtaining Nusselt number is compared with the constant value of Nusselt number 8.23 at constant heat flux for parallel plate and with the Pahor and Turtor [16] theoretical equation which is shown in Fig. 2. Pahor and Turton (1959) equation:

$$\boldsymbol{Nu} = 8.24\left(1 + \frac{3.79}{\boldsymbol{Pe}^2} + \ldots\right), \quad \boldsymbol{Pe} \gg 1 \, \boldsymbol{Pe} = \textbf{Péclet number}; \tag{23}$$

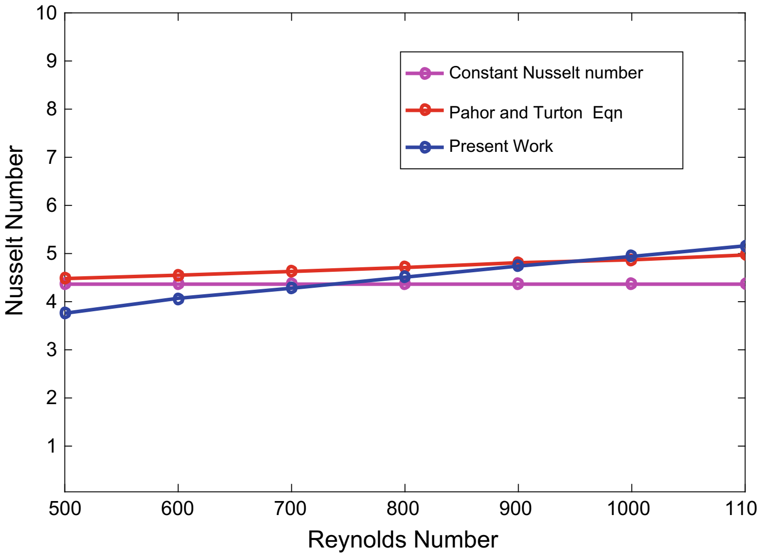

Fig. 2 Comparison of Nusselt number between experimental equation and current study for different Reynolds number of water

$$\boldsymbol{Nu} = 8.118(1 - 0.031\boldsymbol{Pe}), \quad \boldsymbol{Pe} \ll 1 \tag{24}$$

8 Results

Displayed Fig. 3 indicates the effective heat transfer coefficient for Al_2O_3–water, CuO water, SiC–water and TiO_2–water nanofluids at a constant volume fraction of 3%. Other percentages showed similar trends. The result indicates that for all volume fractions of Al_2O_3 nanoparticles, the heat transfer coefficient is higher than other nanofluids. Similar trend has been also described by Mohammed et al. [17] and Koo and Kleinstreuer, [18]. Figure 4 shows the differentiation of pumping power requirement per unit length of Al_2O_3–water nanofluid with different values of heat transfer coefficient and volume concentration. From graphs, it is clear that by the increment of the values of heat transfer coefficient, the pumping power becomes higher in case of same volume concentration. For Ø = 1–5%, the pumping power for Al_2O_3–water nanofluids is reduced by 20–75% compared to water for same heat transfer rate. Other nanofluids provide similar trends. For CuO–water, the pumping power is reduced by 5% to 55%. For SiC–water and TiO_2–water nanofluids, the pumping

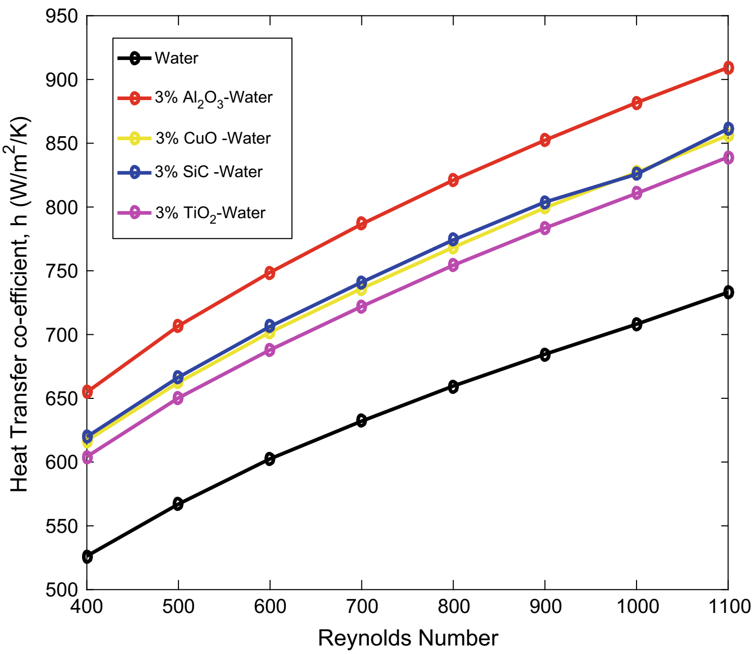

Fig. 3 Variation of heat transfer coefficient with Reynolds number of 3% volume fraction for all nanofluids

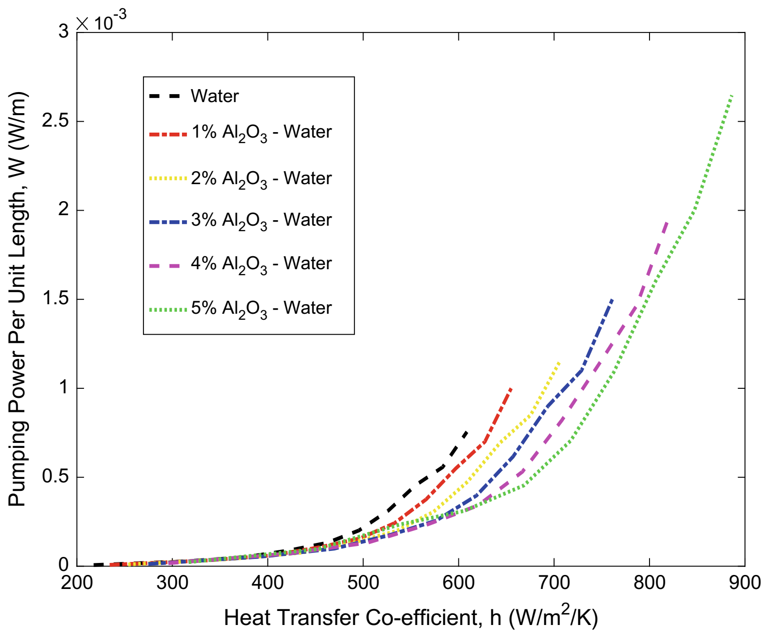

Fig. 4 Variation of pumping power per unit length with heat transfer coefficient for Al_2O_3–water nanofluid

power reduction is almost same 4–45% compared to pure water. Figure 5 shows, the change of pumping power with different heat transfer coefficient at constant volume fraction of 3%. Hence, the results of Fig. 5 indicates that Al_2O_3–water requires lower pumping power in comparison to others for all volume fractions. From Fig. 6, it is analyzed that Nusselt number enhancement ratio is increasing with the increase of volume fraction. Nusselt number enhancement ratio for Al_2O_3 is less than other three nanofluids. From Fig. 7, it is observed that with the increase of volume fractions, heat transfer coefficient enhancement ratio is also increasing. Here, Al_2O_3 shows more enhancement ratio than other three nanofluids, and TiO_2 gives less enhancement ratio comparatively with others. In Fig. 8, the FOM vs. volume fraction graph is shown which indicates that with increasing of volume fraction, FOM is also increasing at constant Reynolds number. For Al_2O_3–water, FOM is higher than other nanofluids; CuO and TiO_2 show almost same result. And more value of FOM indicates more heat transfer enhancement.

To analyze the performance of all used nanofluids, a comparison Table 1 has been introduced below. In this table, for all the nanofluids at a uniform heat transfer coefficient of 700 W/m^2-k for the optimum 3% volume concentration, the pumping power benefit, reduction in volumetric flow rate, pressure difference and mass flow rate have been analyzed for channel. For optimum 3% volume fraction of channel, pumping power benefit of Al_2O_3 is more than other nanofluids, and it is examined that SiC shows less pumping power benefit among them. Similarly, the mass flow

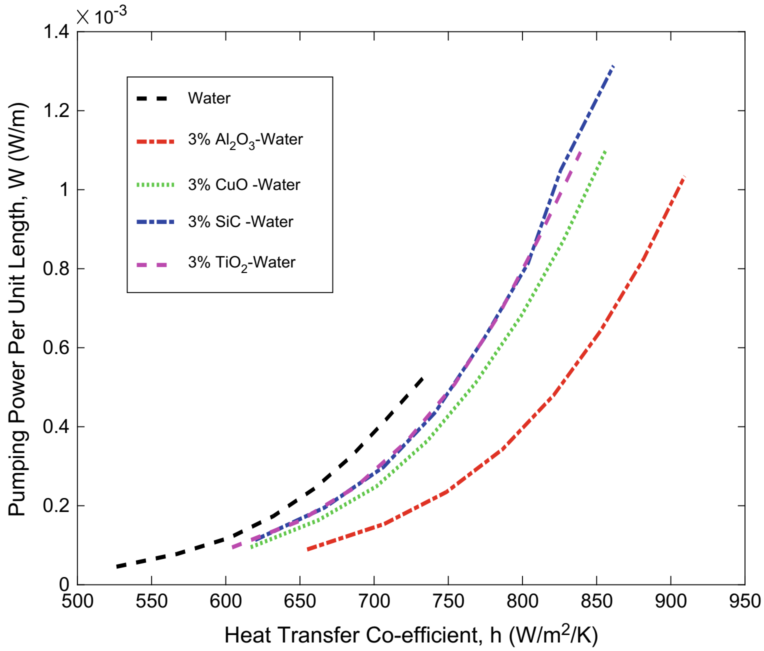

Fig. 5 Differentiation of pumping power per unit length with heat transfer coefficient of nanofluids

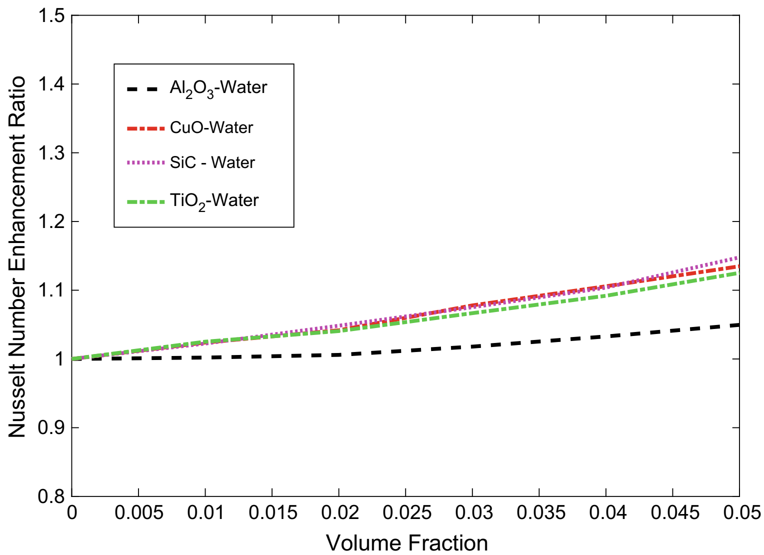

Fig. 6 Variation of Nusselt number enhancement ratio with volume fraction of all nanofluids

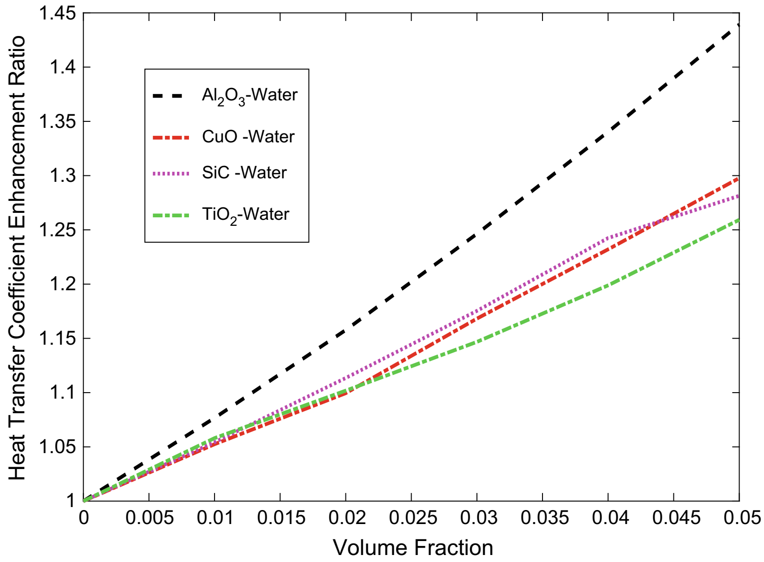

Fig. 7 Variation of heat transfer coefficient enhancement ratio with volume fraction of all nanofluids

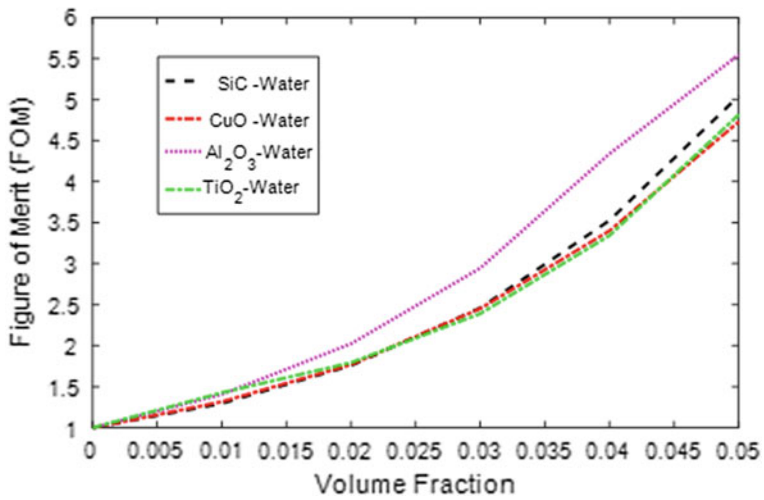

Fig. 8 Variation of FOM with volume fraction of all nanofluids

rate reduction for TiO_2 is less than other nanofluids, and Al_2O_3 gives more reduction in mass flow rate.

Table 1 Differentiation of performance of all the used nanofluids (Ø = 3%) with base fluid water

Type of fluid parameter	Water	3% Al_2O_3	3% CuO	3% SiC	3% TiO_2
Heat transfer coefficient (W/m^2-K)	700	700	700	700	700
Reynolds number	967	488	597	585	630
Nusselt number	9.1	7.50	8.43	8.41	8.4
Pressure loss (Pa/m)	0.7935	0.5032	0.67121	0.71838	0.6856
Pumping power per unit length (W/m)	0.000387	0.000147	0.000249	0.000280	0.000282
Power advantage (W/m)	–	0.000240	0.000138	0.000107	0.000105
Power advantage (%)	–	62%	36%	28%	27.5%
Velocity (m/s)	0.09685	0.05958	0.07275	0.07789	0.07838
Volumetric flow rate (m^3/s)	0.000004868	0.00000299	0.000003657	0.0000003915	0.000003940
Reduction in volumetric flow rate (%)	–	38.47%	24.87%	19.58%	19.06%
Mass flow rate (Kg/s)	0.004849	0.003250	0.004246	0.004160	0.004279
Reduction in mass flow rate (%)	–	33%	12.47%	14.2%	11.77%

9 Conclusion

In the present work, four different nanofluids Al_2O_3–water, CuO–water, SiC–water and TiO_2–water have been studied through typical parallel plates to observe the performance comparison between them on the basis of heat transfer enhancement and the pumping power benefits. Among the four nanofluids, Al_2O_3–water shows more heat transfer enhancement ratio compared to others, and also to get this more heat transfer, Al_2O_3–water required lower pumping power compared to others which is cleared from the graph of FOM. Beside this, Al_2O_3–water also needs lower volumetric/mass flow rate for getting higher heat transfer compared to water and other nanofluids which is also cleared from comparison table. However, TiO_2–water provides lowest performance between all, and CuO–water and SiC–water show almost same performance in heat transfer application on the basis of FOM and pumping power benefit.

References

1. Xuan, Y., Li, Q.: Investigation on convective heat transfer and flow features of nanofluids. ASME J. Heat Transfer **151–155**, 125 (2003). https://doi.org/10.1115/1.1532008
2. Williams, W., Buongiorno, J., Hu, L.-W.: Experimental Investigation of turbulent convective heat transfer and pressure loss of alumina/water and zirconia/ water nanoparticle colloids (nanofluids) in horizontal tubes. ASME J. Heat Transfer **130**(4), 042412 (2008). https://doi.org/10.1115/1.2818775

3. Rea, U., McKrell, T., Hu, L.-W., and Buongiorno, J.: Laminar convective heat transfer and viscous pressure loss of alumina-water and zirconia-water nanofluids. Int. J. Heat Mass Transfer **52**, 2042–2048 (2012). https://doi.org/10.1007/978-3-642-28314-7_65
4. Heris, S.Z., Etemad, S.G., Esfahany, M.N.: Experimental investigation of oxide nanofluids laminar flow convective heat transfer. Int. Commun. Heat Mass Transfer **33**, 529–535 (2006). https://doi.org/10.1016/j.icheatmasstransfer.2006.01.005
5. Yu, W., France, D. M., Smith, D. S., Singh, D., Timofeeva, E. V., Routbort, J. L. Heat transfer to a silicon carbide/water nanofluid. Int. J. Heat Mass Transf. **52**(15–16), 3606–3612. https://doi.org/10.1016/j.ijheatmasstransfer.2009.02
6. Yu, L., Dong, L.: Study of the thermal effectiveness of laminar forced convection of nanofluids for liquid cooling applications. IEEE Appl. Therm. Eng. **3**(10) (2013). https://doi.org/10.1109/tcpmt.2013.2265261
7. Sarkar, J.: Performance of nanofluid-cooled shell and tube gas cooler in transcritical CO_2 refrigeration systems. Appl. Therm. Eng. **31**, 2541–2548 (2011). https://doi.org/10.1016/j.applthermaleng.2011.04.019
8. Ehsan, M.M., Noor, S., Salehin, S., Islam, A.S.: Application of nanofluid in heat exchangers for energy savings. Thermo fluid Modeling for Energy Efficiency Applications, Edn. 1st, Chapter: 4, pp. 73–101 (2015). https://doi.org/10.1016/b978-0-12-802397-6.00004-x
9. Ingole, P.A., Shinde, S.M., Patil, P.A.: Experimental investigation of pumping power and effectiveness of car radiator using Al_2O_3. In: Nanofluid International Conference on Ideas, Impact and Innovation in Mechanical Engineering (ICIIIME 2017) ISSN: 2321–8169, vol. 5(6), pp. 135–141 (2017)
10. Pak, B.C., Cho, Y.: Hydrodynamic and heat transfer study of dispersed fluid with submicron based Al_2O_3 and CuO nanofluids in a triangular duct. J. Disper. Sci. Technol. **34**, 1368–1375 (2013)
11. Nguyen, C., Desgranges, F., Roy, G., Galanis, N., Mare, T., Boucher, S., Anguemintsa, H.: Temperature and particle-size dependent viscosity data for water-based nanofluids—hysteresis phenomenon. Int. J. Heat Fluid Flow **28**(6), 1492–1506 (2007). https://doi.org/10.1016/j.ijheatfluidflow.2007.02.004
12. Maiga, E.B., Nguyen, C.T., Galanis, N., Roy, G.: Heat transfer behaviors of nanofluids in a uniformly heated tube. Super Lattices Microstruct. **35**, 543–557 (2004). https://doi.org/10.1016/j.spmi.2003.09.012
13. Chen, H., Ding, Y., He, Y., Tan, C.: Rheological behaviour of ethylene glycol based titanium nanofluids. Chem. Phys. Lett. **444**(4–6), 333–337 (2007). https://doi.org/10.1016/j.cplett.2007.07.046
14. Maxwell, J.C.: A Treatise on Electricity and Magnetism. Clarendon Press, Oxford (1873)
15. Xuan, Y., Roetzel, W.: Conceptions for heat transfer correlation of nanofluids. Int. J. Heat Mass Transfer **43**, 3701–3707 (2000). https://doi.org/10.1016/S0017-9310(99)00369-5
16. Hatton, A.P., Turton, J.S.: Heat transfer in the thermal entry length with laminar flow between parallel walls at uniform temperature. Int. J. Heat Mass Transfer **5**, 673–679 (1962)
17. Mohammed, H.A., Bhaskaran, G., Shualib, N.H., Abu-Mulaweh, H.I.: Influence of nanofluids on parallel flow square microchannel heat exchanger performance. Int. Commun. Heat Mass Transf. **38**, 1–9 (2011). https://doi.org/10.1016/j.icheatmasstransfer.2010.09.007
18. Koo, J., Kleinstreuer, C.: Impact analysis of nanoparticle motion mechanisms on the thermal conductivity of nanofluids. Int. Commun. Heat Mass Transf. **32**, 1111–1118 (2005). https://doi.org/10.1016/j.icheatmasstransfer.2005.05.014