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ORIGINAL

Heat transfer and pressure drop characteristic of zinc–water nanofluid

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Abstract Development of alternative working fluids with enhanced thermal properties is very much needed to replace conventional fluids. Colloidal solution of some base fluid with solid nanoparticles dispersed in it, which is called as nanofluid, is emerging as a promising alternative heat transfer fluid. Zinc, being ecofriendly material, is selected as dispersed phase in water to develop zinc–water (Zn–H_2O) nanofluid. Zn–H_2O nanofluid is synthesized by single step method and characterized. Thermophysical properties are estimated by available theoretical models. Estimated properties proved that nanofluid is having enhanced thermophysical properties compared to the base fluid due to which nanofluid can become potential working fluid for heat exchanging devices. Synthesized nanofluid is circulated through heat transfer loop to assess its performance in turbulent flow regime and at constant wall temperature condition. Heat transfer coefficient and pressure drop are estimated from experimental results and both are considered as performance evaluation criteria for heat transfer performance assessment. 83 % increase in Nusselt number with 9 % increase in pressure drop is observed for the nanofluid compared to water.

List of symbols

ΔP	Pressure drop (Pa)
ΔT_m	Logarithmic mean temperature difference (K)
A_s	Surface area (m^2)
C_p	Specific heat (J/kg K)
D	Diameter of test section (m)
f	Friction factor
K	Thermal conductivity (W/m K)
L	Length of the test section (m)
Nu	Nusselts number
Re	Reynolds number
T	Temperature (K)
μ	Dynamic viscosity (Pa s)
ρ	Density (kg/m^3)
ϕ	Volume fraction of nanoparticles in base fluid
m	Mass flow rate (kg/s)

Subscripts

f	Fluid
si	Inner surface
so	Outer surface
i	Inlet
o	Outlet
m	Logarithmic mean temperature difference
nf	Nanofluid
p	Particle
c	Cross section

1 Introduction

Use of working fluid is integral part of any heat exchanging devices. Poor thermal properties of working fluid will increase the size of heat exchanger, required pumping power and inventory of the working fluid. It is very much needed to develop the alternative working fluids with better and better thermal properties. Nanofluid is one of the alternatives to conventional working fluids. Nanofluid is a colloidal solution having some base fluid and solid nanoparticles having size less than 100 nm dispersed in it.

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Jang and Choi [1] studied effect of various parameters on nanofluid thermal conductivity and concluded that volume fraction, temperature, and nanoparticle size have a major effect on nanofluid thermal conductivity. Csaba et al. [2] noticed 240 % increase in thermal conductivity of single walled carbon nanotube-water nanofluid over water. Koo and Kleinstreuer [3] have done impact analysis of nanoparticle motion on thermal conductivity of nanofluid and concluded that impact of nanoparticle Brownian motion is much more significant than the thermophoretic and osmophoretic effects at dilute suspension. They also concluded that 0.5 % volume fraction the particle interaction is negligible and while for more than 1 % it is profound. Mintsa et al. [4] studied alumina and copper oxide water nanofluid for thermal conductivity and found that effective K increases with increasing temperature. Zhou and Rui [5] studied specific heat of alumina water nanofluid experimentally and noticed that results are in good agreement with thermal equilibrium model. Murshed et al. [6] presented a study about synthesis, thermophysical properties and its theoretical models, convective heat transfer about nanofluids. They concluded, due to lack of consistency a systematic study related to nanofluid is required. Buongiorno [7] identified Brownian diffusion and thermophoresis as the nanoparticle/base fluid slip mechanisms, reduction of viscosity and consequent thinning of the laminar sublayer for convective heat transfer enhancement. Zeinali et al. [8] studied forced convective heat transfer through tube in laminar flow regime for CuO–water and Al_2O_3 nanofluid and concluded that heat transfer coefficient for Al_2O_3 is higher than CuO. He et al. [9] studied TiO_2–water nanofluid in a vertical copper tube for laminar and turbulent flow regime and noticed considerable enhancement in heat transfer while pressure drop was very close to base fluid. Jaeseen et al. [10] studied Al_2O_3–water nanofluid for laminar and turbulent flow regime in a circular tube and observed single phase h is greater than two phase h. Namburu et al. [11] studied heat transfer to CuO–water nanofluid numerically and found 36 % increase in Nusselt number. Nguyen et al. [12] have studied Al_2O_3–water nanofluid and concluded that the volume fraction of nanoparticle in fluid should be less than 1 % because beyond 1 % there exists a critical temperature beyond which the viscosity strikingly increases. Anoop et al. [13] studied Al_2O_3–water nanofluid having different nanoparticle size and found that enhancement in h for low diameter particle is more than high diameter particle. Chandrashekhar et al. [14] studied Al_2O_3–water nanofluid of 0.1 % volume fraction in tube with wire coil inserts and noticed 12.24 % enhancement in h without any significant pressure drop.

In summary, all the studies indicated, due to addition of nanoparticles in base fluid thermal conductivity increases, viscosity increases, specific heat decreases and density increases. Due to enhanced thermophysical properties nanofluid becomes good alternative coolant. All the studies indicated enhancement in heat transfer coefficient with small pressure drop. Compared to other metals Zinc being ecofriendly material, it is selected for synthesis of nanofluid. The present work aims at experimental study of forced convective heat transfer to Zinc–Water (Zn–H_2O) nanofluid of 0.15 % volume fraction at constant wall temperature condition.

2 Synthesis and characterization of nanofluid

Nanofluids are synthesized by two methods i.e. two step method and one step method. In a two step method nanoparticles are synthesized separately and physically mixed with base fluid. In one step method nanoparticles are synthesized directly in a base fluid. In the present study Zn–H_2O nanofluid is prepared by one step method i.e. metal vapor condensation method.

The photographs of synthesized nanofluid are presented in Fig. 1a, b.

Characterization of synthesized nanofluid is done by X-Ray Difrractometer (XRD) and Scanning Electron Microscope (SEM) and Energy Dispersive Analysis of X-rays (EDAX). Average particle size is estimated from X-Ray diffraction pattern and found to be 42 nm. The color of the nanofluid noticed as dark gray as shown in Fig. 1a, b.

The shape of the particles is characterized by scanning electron microscope (SEM). The particles are filtered out of the fluid and observed under SEM and images are presented here in Fig. 2a–d. Figure 2a indicates the presence of particles in aggregated form. The image shown in Fig. 2b indicates the size of nanoparticle aggregates ranges from 2.83 to 4.10 μm. Figure 2c indicates the shape of aggregated nanoparticles as needles. Figure 2d confirmed the presence of needle like structure of nanoparticles.

Volume fraction of synthesized nanofluid is estimated as 0.15 % from Eq. 3. Density required for estimation of volume fraction is measured by density bottle.

3 Experimental set up and procedure

3.1 Experimental set up

An experimental setup as shown in Fig. 3 is developed to determine inner surface heat transfer coefficient at constant wall temperature condition. The experimental set up consists of test section, constant temperature heating bath, cooler, collecting tank, pump and auxiliary heater etc. Test section is made up of stainless steel tube with inner

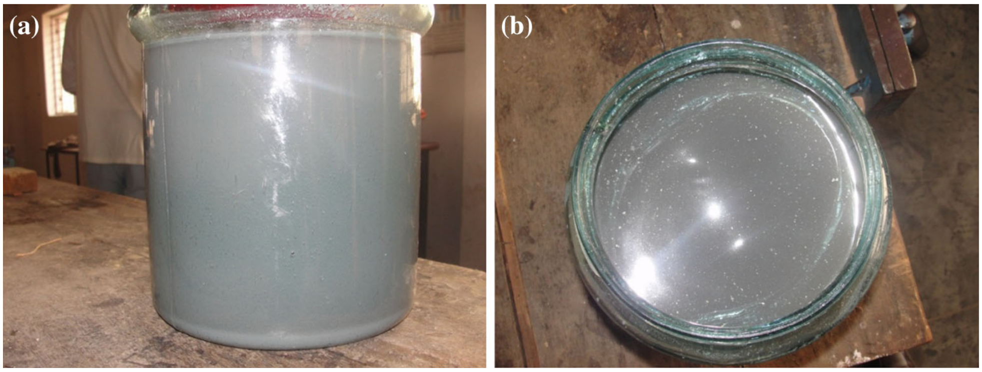

Fig. 1 Photographs of Zn–H_2O nanofluid

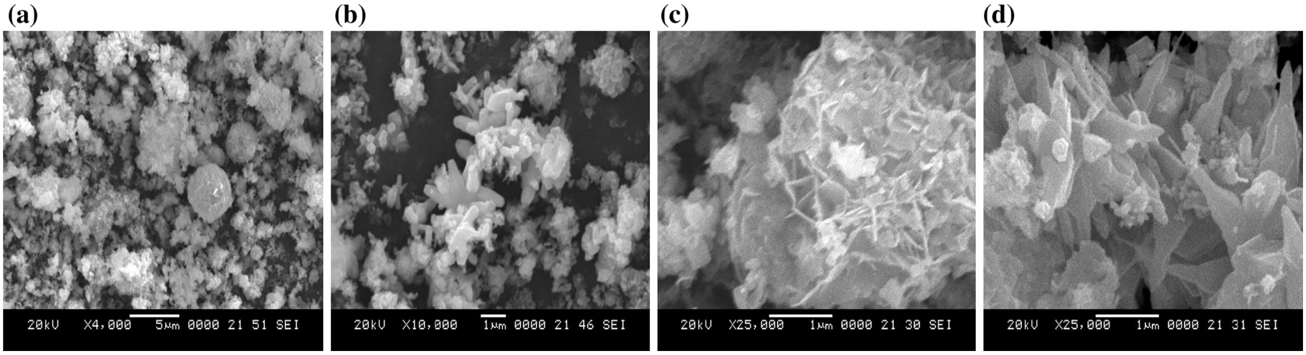

Fig. 2 SEM images of Zn nanoparticles

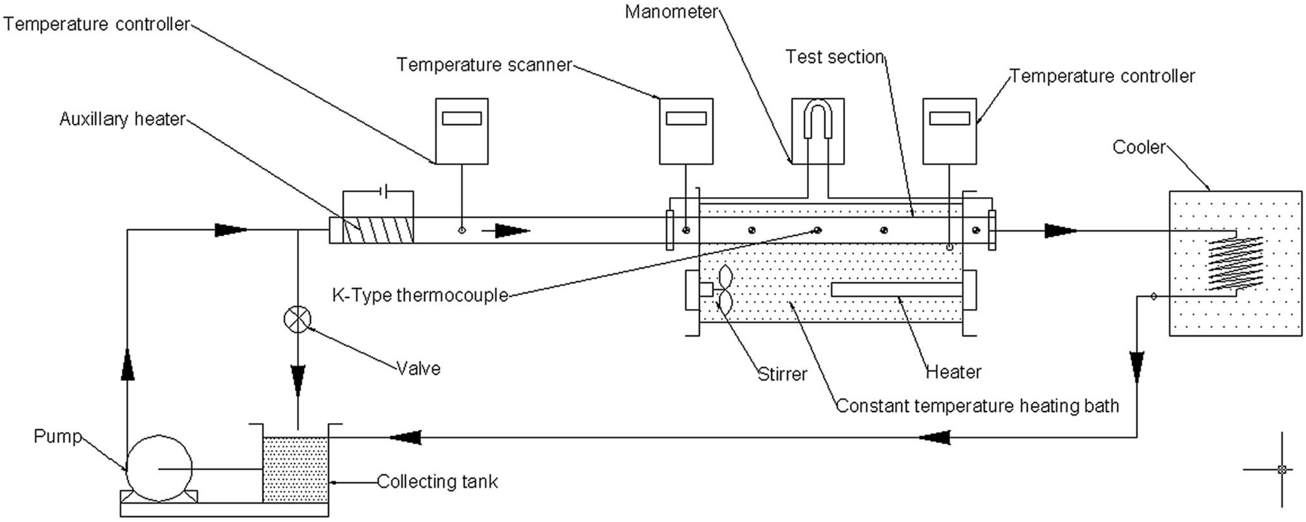

Fig. 3 Experimental setup

diameter 4.93 mm and outer diameter of 6.23 mm and length 0.5 m. A constant temperature heating bath is made up of stainless steel and insulated from outer side with fiber glass insulation. A heater is mounted inside the tank to heat the tank fluid i.e. water. Stirrer is mounted inside the tank to stir the tank fluid continuously to avoid built up of temperature gradient inside the tank fluid. A cooler is used to cool the hot fluid coming out of the test section. A centrifugal pump is used to circulate the fluid in the heat transfer loop. Auxiliary heater is wound around the tube to heat the fluid flowing through the tube to inlet temperature.

A fluid is pumped through test section mounted in a constant temperature heating bath via auxiliary heater and delivered to collecting tank via cooler. With auxiliary heater fluid is heated to inlet temperature which is maintained constant by controlling power to heater by temperature controller by taking feedback from Resistance Temperature Detector (RTD) mounted at outlet section of heater. Test section is mounted in a constant temperature heating bath in such a way that it will get completely immersed in a bath fluid. The temperature of the bath is maintained constant by another temperature controller. Thus constant wall temperature condition of heat transfer is achieved by maintaining the temperature of the fluid around the test section constant. A heated fluid coming out of the test section is cooled in a cooler to recirculate the same fluid. The cooled fluid is discharged to collecting tank.

Two K-Type thermocouples are mounted at inlet and outlet of the test section to measure the temperature of fluid at the respective locations. In addition four K-Type thermocouples are mounted on the surface of test section to measure surface temperature. Temperature is measured with ±3 % accuracy. Inverted U tube air filled manometer is used to measure pressure drop across the test section. A mass flow rate of the fluid is measured by collecting the fluid in a particular time and weighing with micro-weighing machine. Uncertainty analysis of mass flow rate measurement has been done. The measured value of m is accurate within ±3.45 % with 95 % confidence level.

3.2 Experimental procedure

A matrix of experiments has been performed on 0.15 % volume fraction of Zn–H_2O nanofluid and water. Observations are noted at steady state condition for inlet temperature range 30–35 °C, surface temperature range 70–90 °C and Reynolds number range 2,000–20,000 for both water and Zn–H_2O nanofluid. Following equations have been used for data reduction to calculate heat transfer coefficient for water and nanofluid. Heat gained (q) by fluid while flowing through test section is calculated by

$$q = mC_p(T_o - T_i)$$

With measured value of outer surface temperature, inner surface temperature is calculated from

$$q = \frac{T_{so} - T_{si}}{\ln(r_o/r_i)/2\pi LK_m}$$

Where K_m is thermal conductivity and L is length of test section wall. With inner surface temperature logarithmic mean temperature difference is calculated from

$$\Delta T_m = \frac{(T_{si} - T_i) - (T_{si} - T_o)}{\ln((T_{si} - T_i)/(T_{si} - T_o))}$$

Heat transfer coefficient is calculated by energy equation considering the temperature of the fluid flowing through the test section vary logarithmically from

$$mC_p(T_o - T_i) = h_{si}A_{si}(\Delta T_m)$$

Thermophysical properties for nanofluid are estimated by using available theoretical models. Yimin and Wilfried [15] presented a model of Wasp (Eq. 1) to calculate K_{nf} and Einstein model (Eq. 2) to calculate μ_{nf}. ρ_{nf} (Eq. 3) and $C_{p\ nf}$ (Eq. 4) is calculated as per mixure theory.

$$\frac{K_{nf}}{K_f} = \frac{K_p + 2K_f - 2\varnothing(K_f - K_p)}{K_p + 2K_f + \varnothing(K_f - K_p)} \tag{1}$$

$$\mu_{nf} = (1 + 2.5\emptyset)\mu_f \tag{2}$$

$$\rho_{nf} = (1 - \emptyset)\rho_p + \emptyset\rho_f \tag{3}$$

$$C_{p_{nf}} = \frac{\emptyset(\rho C_p)_p + (1 - \emptyset)(\rho C_p)_f}{\emptyset\rho_p + (1 - \emptyset)\rho_f} \tag{4}$$

Reynolds number and Nusselt number are calculated from following formulae.

$$Re = \frac{mD}{A_c\mu_{nf}}$$

$$Nu = \frac{hD}{K}$$

Thermophysical properties are considered at bulk mean temperature for calculating dimensionless numbers and data reduction.

4 Results and discussion

4.1 Heat transfer characteristic

Thermo physical properties for nanofluid are estimated from the theoretical models and the values indicated increase in K, increase in ρ, decrease in C_p, and increase in μ over the base fluid. As there is no consistency in K estimated from different theoretical models, one cannot conclude exactly about the enhancement potential available in the nanofluid hence experimental study solely on heat transfer is required. The experimental observations in the form of graph of Re versus Nu and Re versus ΔP are presented in Figs. 4 and 5 respectively. The graph indicated increase in Nu and ΔP as Re increases for both water and nanofluid which is a general trend for any fluid as per heat transfer theories.

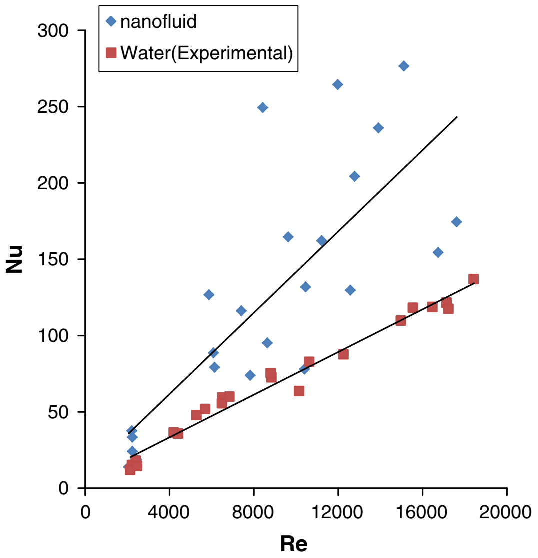

Fig. 4 Graph of Re versus Nu calculated from experimental observations

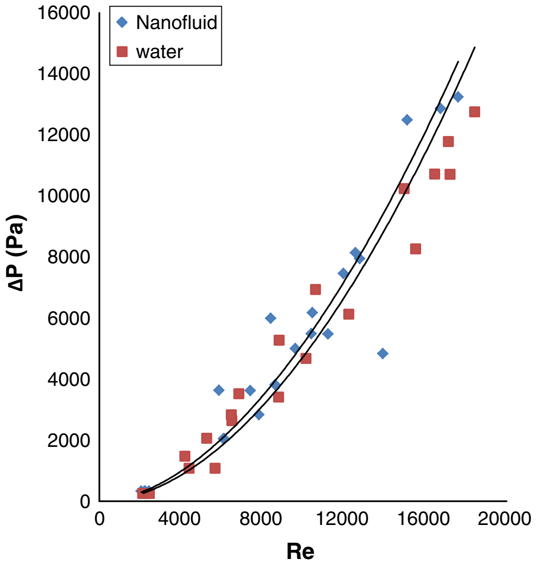

Fig. 5 Graph of Re versus ΔP calculated from experimental observations

Appropriate curve is fitted in the scatter diagram of experimental results by regression analysis and the curves are as shown in Figs. 4 and 5. When regression analysis with 75 % confidence level is performed for heat transfer characteristics, it is observed that the best fitted line for water is not overlapping the confidence band of best fitted line of nanofluid and R^2 value is more than 0.6 for both water and nanofluid which indicates that there exist a correlation amongst the experimental results. Even though the measurements are noted with same measuring instruments and set up, for both water and nanofluid, nanofluid has shown more uncertain behavior than water. The equations of best fitted curves along with correlation coefficient (R) for nanofluid and water are presented by Eqs. (5), (6), (7), and (8).

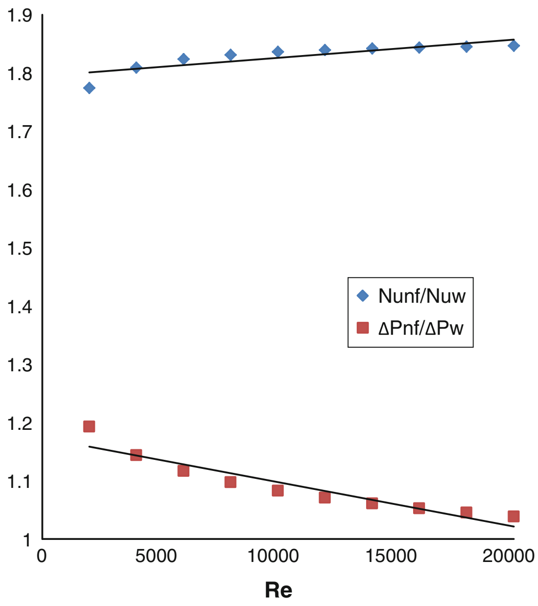

Fig. 6 Graph of enhancement ratios versus Re

$$Nu_{nf} = 0.013Re_{nf} + 8.310 \quad \text{With } R^2 = 0.626 \tag{5}$$

$$Nu_{w} = 0.007Re_{w} + 5.341 \quad \text{With } R^2 = 0.975 \tag{6}$$

$$\Delta P_{nf} = 2.86 \times 10^{-4} Re_{nf}^{1.81} \quad \text{With } R^2 = 0.969 \tag{7}$$

$$\Delta P_{w} = 1.52 \times 10^{-4} Re_{w}^{1.87} \quad \text{With } R^2 = 0.964 \tag{8}$$

For a fixed Reynolds number, with the above equations the ratio of Nu_{nf}/Nu_w and $\Delta P_{nf}/\Delta P_w$ is estimated. To have a good understanding about the heat transfer and pressure drop enhancement, the graph of Re versus Nu_{nf}/Nu_w and $\Delta P_{nf}/\Delta P_w$ is plotted which is presented in the Fig. 6. The range of Re considered is 2,000–20,000 in the step of 2,000 for estimating the ratios. The graph shows that the ratio of Nu_{nf}/Nu_w is always greater than $\Delta P_{nf}/\Delta P_w$ indicating higher heat transfer enhancement than pressure drop enhancement. Nu_{nf}/Nu_w and $\Delta P_{nf}/\Delta P_w$ is having the value greater than one which indicates that heat transfer and pressure drop for the nanofluid is always more than water. The increasing trend of Nu_{nf}/Nu_w and decreasing trend $\Delta P_{nf}/\Delta P_w$ as per Re indicates that the nanofluid is suitable for higher mass flow rates. At higher Re, ΔP_{nf} approaches to ΔP_w indicating requirement of same pumping power as that of water. A large ratio of Nu_{nf}/Nu_w compared to small $\Delta P_{nf}/\Delta P_w$ indicates that nanofluid is having high heat transfer enhancement with negligible pressure drop.

Figure 6 clearly indicates that enhancement in Nusselt number is higher than enhancement in pressure drop indicating augmentation of heat transfer with negligible ΔP. The reasons of enhancement in heat transfer and pressure drop are discussed below.

Nanoparticles are having high surface energy and area to volume ratio. Nanoparticles are always in aggregated form due to Van Der Waal's forces of attraction when dispersed in base fluid. At lower Re, nanoparticles will be flowing in aggregated form along with the fluid. Nanoparticles separate out from aggregates as per Re due to increased turbulence. As per study of King [16], higher the velocity, higher the turbulence level and greater the ability of the carrier fluid to keep the particle in suspension. It is the upward motion of eddy currents transverse to the main direction of flow of slurry that is responsible for maintaining the particle in suspension. At very high turbulence the suspension is almost homogeneous.

Buongiorno [7] identified Brownian motion and thermophoresis has a measure impact on nanofluid thermal conductivity. As Re increases, due to increased turbulence nanoparticles will get separated from aggregates. The size of agglomerate goes on decreasing as Re increases thereby increasing homogeneity of nanofluid. Due to increased homogeneity k for nanofluid increases thereby increasing heat transfer coefficient. Nanoparticles cannot penetrate into laminar sublayer due to inertia but due to Brownian motion and thermophoresis K of the fluid in laminar sublayer will be more which enhances heat transfer coefficient. When particles are flowing in aggregated form gravity effects and settling as per stokes law play a significant role thereby reducing the turbulence and increasing tendency of settling which reduces h for nanofluid at lower Re.

Pressure drop characteristic for water and nanofluid is shown in Fig. 5. Both fluids are having almost same pressure drop for the range of Re considered. Pei and James [17] calculated 0.2845 nm as a thickness of water nanolayer around nanoparticles. Due to viscous effects in laminar sublayer frictional drag is developed and pressure drops along the length of the pipe. Surface to fluid interaction develops nanolayer around the nanoparticles while flowing alongwith the fluid. The wall of the pipe experiences same frictional drag for nanofluid as that of base fluid due to nanolayer around the nanoparticle and on the wall. This is the reason both the fluids are having almost same pressure drop.

5 Conclusions

Heat transfer and pressure drop characteristic of Zn–H_2O nanofluid has been studied experimentally for 0.15 % volume fraction and Reynolds number range 2,000–20,000 at constant wall temperature condition, when the fluids are being heated. Nusselt number and pressure drop for the nanofluid is greater than water for the considered range of Re. When heat transfer and pressure drop characteristic of the nanofluid is compared with water for the considered range of Reynolds number, 82 % enhancement in Nusselt number with 9 % enhancement in pressure drop is observed.

Uncertainty analysis of experimental results of heat transfer characteristic for nanofluid and water indicated that the nanofluid is having more uncertain behavior than water even though the observations are taken with same set up and measuring instruments for both water and nanofluid. This indicates that further investigation is required before commenting on potential use of the nanofluid for heat transfer applications.

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