Journal of Mechanical Science and Technology 29 (5) (2015) 2177~2185
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-015-0438-x

Miniaturization of automobile radiator by using zinc-water and zinc oxide-water nanofluids †

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(Manuscript Received June 3, 2014; Revised September 21, 2014; Accepted January 15, 2015)

Abstract

High performing fluids for energy conservation and energy efficiency replace conventional heat transfer fluids. This study relates to the development of an alternative heat transfer fluid called as nanofluid. Nanofluid is a dispersion of solid nanoparticles in a base fluid having enhanced thermal properties compared to base fluid. Zinc and Zinc oxide, being eco-friendly and having easy nanoparticle production processes, are considered for the synthesis of nanofluids of different volume fractions. In this experimental study related to heat transfer, the preparation of Zinc-water (Zn-H_2O) nanofluid involves the single step method, while the preparation of Zinc oxide-water (ZnO-H_2O) uses the two-step method. Six nanofluids comprising of three Zn-H_2O and three ZnO-H_2O in different volume fractions are tried for this study. Conduct an experimental study to calculate the enhancement of heat transfer coefficient and pressure drop compared to water. Apply the performance evaluation criterion to assess the heat transfer performance of the considered nanofluids. Amongst the six nanofluids, Zn-H_2O nanofluid of 0.5% volume fraction proves to have the best heat transfer performance. Then, assess this high performing fluid theoretically in an automobile radiator to get benefits of its use. If by replacing the water with Zn-H_2O nanofluid of 0.5% volume fraction it is estimated that the size of the radiator, inventory of the fluid, and pumping power is reduced, thus, making this nanofluid an energy efficient fluid for the engine cooling system.

Keywords: Enhancement; Heat transfer coefficient; Nanofluid; Performance evaluation criteria; Pressure drop

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1. Introduction

The coolant of an engine cooling system (ECS) consumes about 30% of the heat generated in the engine and the same quantity of heat is lost in the automobile radiator to atmospheric air. Higher heat removal from ECS will decrease the thermal efficiency of the engine and low heat removal will overheat the engine. Therefore, we need to develop alternative coolants, with enhanced thermal properties, to make the ECS compact and energy efficient. Coolant side heat transfer coefficient and pressure drop, are important parameters which affect the energy efficiency of the automobile radiator. Poor thermo- physical properties of the coolant will increase the heat transfer surface area, inventory of the coolant, and pumping power. Nanofluid, which is a colloidal solution of solid nanoparticles and base fluid, will become the future coolant for ECS due to its enhanced thermal properties over conventional coolants. However, a detailed study about synthesis, heat transfer performance, and benefits of replacement in the radiator is necessary before arriving at the final decision regarding the use of nanofluid in ECS.

Buongiorno [1] studied the contribution of different parameters on the enhancement of thermal conductivity of nanofluid. Thermal conductivity of nanofluid is higher than base fluid because of Brownian motion, thermophoresis, diffusiophoresis, formation of nano layer on nanoparticle, and clustering of nanoparticles. Dalkilic et al. [2] studied different nanofluids and concluded that the heat transfer performance of nanofluid is more than of base fluid, but no definitive agreement emerged on the thermal conductivity and viscosity of the nanofluids. Naraki et al. [3] studied the contribution of different parameters in enhancement of the overall heat transfer coefficient. The air volumetric flow rate has 42% contribution in the overall heat transfer coefficient of CuO/water nanofluid. Nanofluid volumetric flow rate, inlet temperature, and concentration of nanofluid have 23%, 22%, and 13% contribution in the overall heat transfer coefficient of CuO/water nanofluid, respectively. Peyghambarzadeh et al. [4] studied CuO-water and Fe_2O_3 nanofluids at different velocities and inlet temperatures in a car radiator and concluded that the overall heat transfer coefficient increases, while the liquid inlet temperature decreases. Leong et al. [5] concluded that if nanofluid replaces ethelene glycol, about 18.7% frontal area of the radia-

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† Recommended by Associate Editor Taesung Kim

tor reduces. Sebastien et al. [6] concluded that performance evaluation criteria (PEC) for SiO_2-H_2O nanofluid is less than 1 and for ZnO-H_2O nanofluid approaching to 1, indicating that ZnO-H_2O nanofluids are suitable for heat transfer applications.

All studies have shown enhancement in heat transfer without appreciable enhancement in pressure drop. Due to enhanced thermo-physical properties, nanofluids will become the future working fluid for heat transfer applications. Compared to other metals like copper and aluminum, zinc has a low melting point, so the production process of zinc oxide nanoparticles by high temperature oxidation will become easy and cheap. The selection of Zinc oxide as a solid nanomaterial for the development of Zn-H_2O nanofluid is because it is a stable and environment friendly material [7]. In this study, we intend to present the development of Zn-H_2O and ZnO-H_2O nanofluid in different volume fractions, its heat transfer performance, and the benefits of its use in an automobile radiator. The different steps followed to carry out the present study are thus:

(1) The synthesis of nanofluids of different volume fractions.

(2) Circulating the nanofluids in an experimental set up, at different inlet temperatures, surface temperatures, and mass flow rates to determine the heat transfer coefficient and pressure drop for different nanofluids.

(3) Applying performance evaluation criteria to judge the best performing fluid.

(4) Assessing benefits of replacement of water by nanofluid in an automobile radiator.

2. Synthesis of nanofluids

One-step method and the two-step method are the methods to synthesize nanofluid. In the one- step method, the nanoparticles are synthesized in the base fluid itself, while in the two-step method; the nanoparticles are separately synthesized and then are physically mixed in the proper volume proportions to get the required nanofluid.

Zinc-water nanofluid is synthesized using the metal vapour condensation method. Using this method, heat the pure zinc metal to boiling temperature (907°C) and directly condense the vapours into the water in a chamber isolated from atmospheric air. The metallic vapour of the zinc will disperse in the water to form a colloidal solution called nanofluid. The size of the nanoparticle is determined as 42 nm from the diffraction pattern obtained using an X-Ray diffractometer. With measured density of nanofluid, the volume fraction of the synthesized nanofluid is determined as 1.2% from Eq. (1). From the nanofluid of $\phi = 1.2\%$, other nanofluids of $\phi = 0.15\%$, 0.25%, and 0.5% are prepared through dilution and ultra-sonication.

$$\rho_{nf} = \left(1-\varnothing\right)\rho_p + \varnothing\rho_f . \tag{1}$$

Synthesis of Zinc oxide-water nanofluid using the two- step method: The high temperature oxidation of zinc vapours at the outlet of the tube furnace synthesizes ZnO nanoparticles. The size of the ZnO particle is determined as 32nm. Then, physically mix the synthesized ZnO particles in the water and ultrasonicate it to get the ZnO-H_2O nanofluid. From Eq. (2), we can estimate the required mass of nanoparticles to mix in the water to get nanofluid of different volume fractions such as 0.15%, 0.25%, and 0.5%.

$$m_p = \left(\frac{\varphi}{1-\varphi}\right)\left(\frac{\rho_p}{\rho_w}\right)m_w . \tag{2}$$

Koo and Kleinstreuer [8] have done impact analysis of nanoparticle motion on thermal conductivity of nanofluid, and concluded that the impact of nanoparticle Brownian motion is much more significant than the thermophoretic and osmophoretic effects at dilute suspension. They also concluded that at 0.5% volume fraction, the particle interaction is negligible, and while for more than 1%, it is profound. Hence, for the present study, we are taking three volume fractions of less than 0.5% into consideration. We will study 0.15%, 0.25%, and 0.5% volume fractions of Zn-H_2O and ZnO-H_2O nanofluids to determine h and ΔP.

3. Experimental method

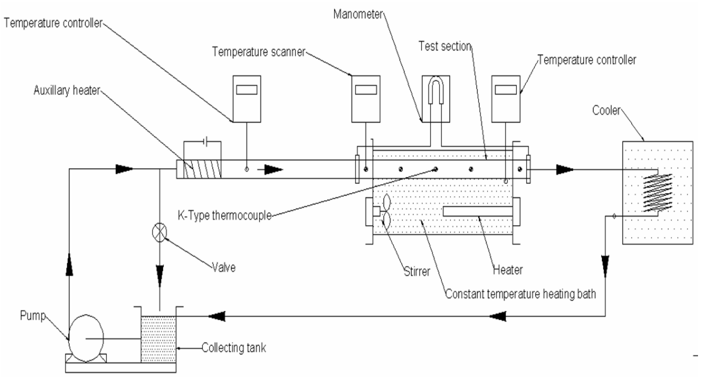
3.1 Experimental set up

Fig. 1(a) shows the experimental set up to determine the h and ΔP of different nanofluids. All nanofluids will be circulated through the set up.

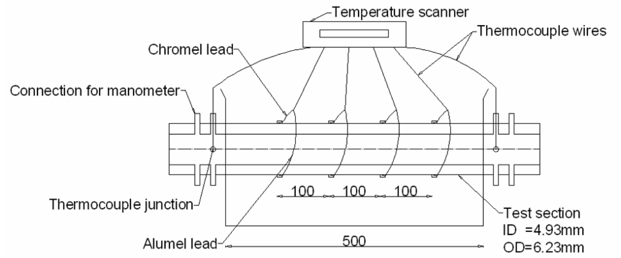
A fluid is pumped through the test section made of a stainless steel (SS304) tube with an inner diameter of 4.93 mm and outer diameter of 6.23 mm and length 0.5 m. The details of the test section are shown in Fig. 1(b). Immerse the test section completely into the constant temperature bath. In the auxiliary heater, heat the fluid to the inlet temperature, which is maintained constant by controlling the power to heater by temperature controller by taking feedback from the resistance temperature detector (RTD) mounted at the outlet section of the heater. Mount two K-Type thermocouples at the inlet and outlet of the test section to measure the temperature of the respective locations. In addition, mount four K-Type thermocouples on the surface of the test section to measure the surface temperature. Temperature is indicated with ±3% accuracy. Use the inverted U tube air filled manometer to measure the pressure drop across the test section. Measure the mass flow rate of the fluid by collecting the fluid in a particular time and weigh it using the micro-weighing machine. Do the uncertainty analysis of the mass flow rate measurement. The measured value is accurate within ±3.45% with 95% confidence level.

3.2 Experimental procedure

Perform experiments on different volume fractions of nanofluids and water. Note the observations at steady state condition for inlet temperature ranging 30-35°C, surface tempera-



(a)



(b)

Fig. 1. (a) Experimental setup for determination of h and ΔP; (b) details of test section.

ture ranging 70-90°C, and Reynolds number ranging 4000 to 20000 for all the fluids. Try different volume fractions such as 0.15%, 0.25%, and 0.5% of the Zn-H_2O and ZnO-H_2O nanofluids in the set up. Reduce the experimental observations, taken for water and six nanofluids, to get the inner side heat transfer coefficient (h). Following is a step-by- step procedure to determine h and ΔP. Take all thermo- physical properties of water required for calculation at the bulk mean temperature. The range of the bulk mean temperature is 34 to 47°C.

Step 1. Viscosity of nanofluid is estimated from Eq. (3) proposed by Batchelor [9] considering the effect of Brownian motion on the viscosity

$$\mu_{nf} = \left(1 + 2.5\varnothing + 6.5\varnothing^2\right)\mu_w . \tag{3}$$

Step 2. $Re = \dfrac{mD}{A_c \mu_{nf}}$. (4)

Step 3. Cengel Y. A. [10] presented Bhatti and Shah equation (5) for calculation of entry length (L_h) for turbulent flow.

$$L_h = 1.359\, D\, Re^{0.25} . \tag{5}$$

Step 4. Effective length (L_e) which is to be considered for calculation of inner side average heat transfer coefficient is calculated from Eq. (6)

$$L_e = L_t - L_h . \tag{6}$$

Step 5. As per mixture theory, specific heat for nanofluid is determined from Eq. (7)

$$C_{p_{nf}} = \frac{\varnothing\left(\rho C_p\right)_p + \left(1-\varnothing\right)\left(\rho C_p\right)_w}{\varnothing \rho_p + \left(1-\varnothing\right)\rho_w} . \tag{7}$$

Step 6. Heat gained (q) by nanofluid while flowing through tube is estimated from energy equation (Eq. (8))

$$q = m_{nf}\, Cp_{nf}\left(T_0 - T_i\right) . \tag{8}$$

Step 7. With measured value of outer surface temperature, the inner surface temperature is calculated from Eq. (9)

$$q = \frac{T_{so} - T_{si}}{\ln\left(r_o / r_i\right) / \left(2\pi L_e K_t\right)} \tag{9}$$

(where K_t is thermal conductivity of test section wall) as outside surface temperature of the test section is measured rather than fluid temperature, hence outside convective resistance is not considered.

Step 8. Logarithmic mean temperature difference (ΔT_{LMTD}) is calculated from Eq. (10)

$$\Delta T_{LMTD} = \frac{\left(T_{si} - T_i\right) - \left(T_{si} - T_o\right)}{ln\left(T_{si} - T_i\right) / \left(T_{si} - T_o\right)} . \tag{10}$$

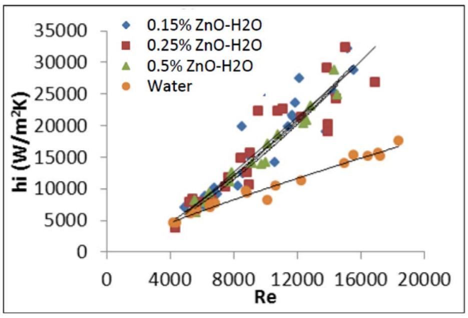


Fig. 2. Scatter diagram of Re versus h for ZnO-H_2O nanofluid.

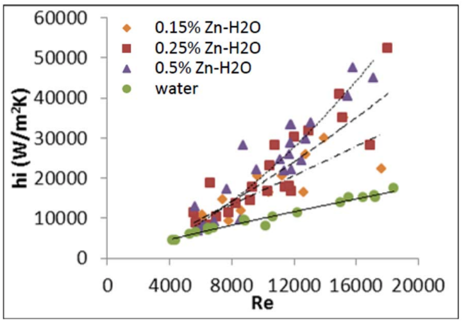


Fig. 3. Scatter diagram of Re versus h for Zn-H_2O nanofluid.

Step 9. Nanofluid side surface heat transfer coefficient is calculated from

$$q = h_{nf} A_{si} \Delta T_{LMTD} . \tag{11}$$

4. Results and discussion

4.1 Heat transfer characteristics of nanofluids

With experimental observations, the heat transfer coefficient and pressure drop is determined as per the procedure explained in Sec. 3.2 of this paper. The scatter diagram plotted is shown in Figs. 2 and 3 for different volume fractions of ZnO-H_2O and Zn-H_2O, respectively. Based on the nature of the experimental data of the scatter diagram, we decide to fit the power law relation amongst the data points by regression analysis. The trend line of each nanofluid and water shows a general trend of increase in h with increase in Re.

The equation of best fitted curve for the experimental data takes the form presented by equation Eq. (12). We have also presented the value of coefficient of determination (R^2) of curve fitting in the equation. Table 1 presents the value of constants a, b, c obtained by the curve fitting technique for different nanofluids. In the present experimental work, for all nanofluids R^2 is greater than 0.72. It indicates that there exists a strong correlation amongst the data.

$$h_i = aRe^b \quad with \quad R^2 = c . \tag{12}$$

Table 1. The value of a, b, c in Eq. (12) obtained by regression analysis for different nanofluids.

	Water	Zn-H_2O			ZnO-H_2O		
		ϕ = 0.15%	ϕ = 0.25%	ϕ = 0.5%	ϕ = 0.15%	ϕ = 0.25%	ϕ = 0.5%
a	0.773	0.996	0.111	0.006	0.073	0.075	0.042
b	1.025	1.058	1.307	1.627	1.338	1.332	1.390
c	0.967	0.725	0.778	0.837	0.896	0.876	0.959

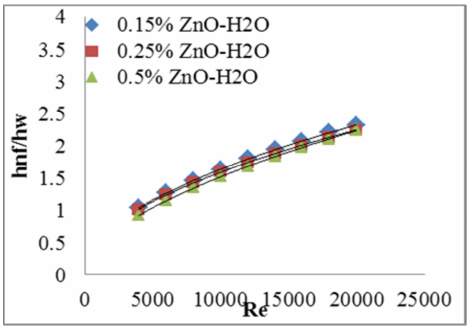


Fig. 4. Trendlines of best fitted curves in the experimental data for ZnO-H_2O nanofluid.

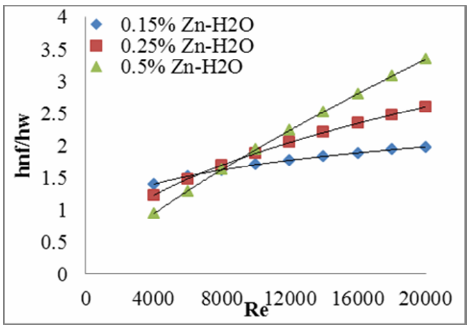


Fig. 5. Trendlines of best fitted curves in the experimental data for Zn-H_2O nanofluid.

For a fixed Re, it is necessary to compare the enhancement ratio of nanofluid of different volume fractions to get a better understanding about the heat transfer performance. With the equations of best fitted curves, the enhancement ratio (h_{nf}/h_w) for the Reynolds number ranging from 4000 to 20000 in steps of 2000 is calculated, and the graph of h_{nf}/h_w versus Reynolds number is shown in Figs. 4 and 5.

Both, Figs. 4 and 5 indicate that heat transfer enhancement increases with increase in Re for nanofluids of all volume fractions. We will now discuss the reason. When we disperse nanoparticles in a fluid, they remain in an aggregated form due to Van Der Waal's forces of attraction. Turbulence in the fluid flow increases with increase in Re. The nanoparticles separate from the agglomerates due to increased turbulence making the fluid flow more homogeneous. Decreased agglomerate size and increased homogeneity of the fluid enhances the Brownian motion thereby, increasing the thermal conductivity of the fluid and thermal dispersion. Buongiorno [1] observed Brownian motion to be the measure contributor

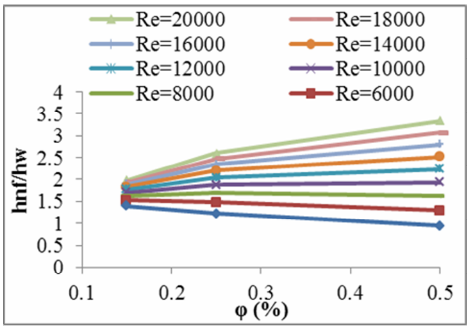


Fig. 6. Variation of h_{nf}/h_w as per volume fraction for ZnO-H_2O nanofluid.

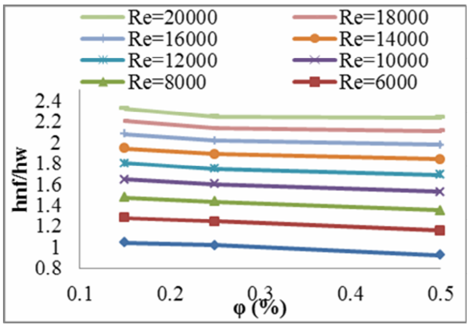


Fig. 7. Variation of h_{nf}/h_w as per volume fraction for Zn-H_2O nanofluid.

to enhancement in the thermal conductivity of nanofluids, and due to the enhanced k, the heat transfer coefficient increases as per Re. The theory explained by King [11] supports the above explanation. As per his study, higher the velocity, higher is the turbulence level and greater the ability of the carrier fluid to keep the particle in suspension. It is the upward motion of the eddy currents transverse to the main direction of the flow of slurry that is responsible for maintaining the particle in suspension. The study of Kole and Dey [12] also supports the explanation of enhanced h with increase in Re. As per their study, the high thermal conductivity enhancement in ZnO-EG nanofluid is believed to be associated with the superior fragmentation and dispersion of ZnO nanoparticle clusters in EG due to the prolonged period of sonication (> 60 hours). The fragmentation of nanoparticle clusters into smaller ones leads to significant enhancement in the thermal conductivity of nanofluids.

Figs. 6 and 7 indicate that enhancement in h increases for Zn-H_2O nanofluid and decreases for ZnO-H_2O nanofluid with increase in volume fraction. We will now discuss the reasons for this kind of opposite behavior.

With increase in volume fraction, the aggregation tendency and viscosity of the fluid increases for both the nanofluids. Zinc oxide, being non-metal, has a very low k compared to zinc. For Zinc oxide nanofluid, due to increased aggregate size, the Brownian motion reduces which makes the thermal conductivity of ZnO-H_2O to reduce with increase in volume fraction, and in addition, the viscosity increases which reduces the turbulence and thermal dispersion. The increased size of aggregates of ZnO and its low thermal conductivity act as barriers to heat transfer near the wall. Gharagozloo [13] concluded that enhancement in thermal conductivity increases with increase in volume fraction, but the enhancement is temporal. They also observed the fast aggregation of higher concentration fluid compared to lower concentration fluid, and the aggregation reduces thermal diffusion. Karthikeyan et al. [14] measured k for 0.8% and 0.3% volume concentrations of 8nm for CuO particles in water and found enhancement of 23% and 17%, respectively, and the enhancement decreases to 0% over 20 minutes, which indicates that the enhancement is temporal.

Thermal conductivity is one of the six parameters responsible for heat transfer enhancement. Due to increased volume fraction, thermal conductivity enhances temporarily but other parameters gets affected significantly reducing heat transfer coefficient with increase in volume fraction. The reduced heat transfer near wall due to low k of ZnO and reduced Brownian motion due to higher aggregate size reduces enhancement in h with increase in volume fraction.

For Zn-H_2O nanofluid, the enhancement in h increases with increase in volume fraction, and this enhancement are profound. As the volume fraction increases due to the increased size of aggregates and higher conductivity of zinc compared to zinc oxide, near wall heat transfer increases and quantity of thermal dispersion is also more in comparison to ZnO-H_2O nanofluid, so h increases. The results of Gosselin [15] are consistent with the present study. As per his study, if the particles are few, the augmentation of effective thermal conductivity is small, but the convective movements are strong due to the low viscosity. On the other hand, too large a concentration of particles breaks the flow, but also increases the thermal conductivity.

4.2 Pressure drop characteristic

The experimental values of ΔP obtained for water and all the nanofluids is plotted to get the graph of Re versus h shown in Figs. 8 and 9. Considering the scatter of the data we can fit power law relation by regression analysis.

The best fitted equation takes the form as shown in Eq. (13). The coefficients l, m, n (coefficient of determination) by regression analysis for different nanofluids is presented in Table 2.

$$\Delta P = lRe^{m} \qquad with\, R^2 = n\,. \tag{13}$$

To compare the pressure drop characteristic of different nanofluids for a fixed Re, the graph of Re versus ΔP is plotted with calculated values of ΔP from the equation of best fitted curve. We are presenting the graphs in Figs. 10 and 11 for ZnO-H_2O and Zn-H_2O nanofluids, respectively.

All nanofluids show a general trend of increasing Δp with increasing Re. The variation of ΔP, for all volume fractions, is within ±10% for ZnO-H_2O nanofluid and within ±5% for Zn-

Table 2. The values of l, m, n in Eq. (13) obtained by regression analysis for different nanofluids.

Water		Zn-H2O			ZnO-H2O		
		φ = 0.15%	φ = 0.25%	φ = 0.5%	φ = 0.15%	φ = 0.25%	φ = 0.5%
l	0.006	0.012	0.011	0.014	0.005	0.003	0.003
m	1.405	1.337	1.349	1.325	1.442	1.49	1.511
n	0.949	0.719	0.879	0.922	0.968	0.88	0.926

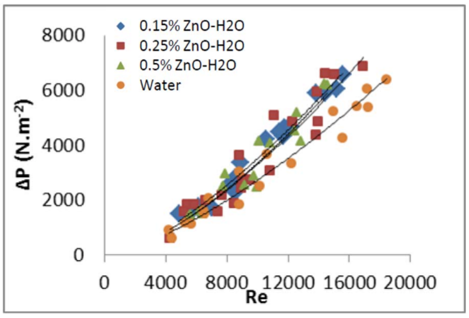


Fig. 8. Scatter diagram of Re verses ΔP for ZnO-H_2O.

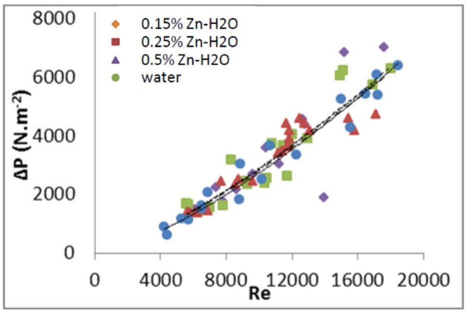


Fig. 9. Scatter diagram of Re verses ΔP for Zn-H_2O.

H_2O nanofluid. Based on the trends it can be concluded that enhancement in ΔP is negligible for all the nanofluids. The small increase is due to particle-particle, particle-fluid, and particle-wall interactions. We shall now discuss the reason for the nearly same pressure drop for water and nanofluid.

Water gets adsorbed over the surface of nanoparticles forming a nanolayer of water on the nanoparticle surface. Pei and James [16] calculated 0.2845 nm as the thickness of the water nanolayer around nanoparticles based on a model by Wang et al.

Due to the nanolayer around the nanoparticle and on the wall, the wall of the pipe experiences the same frictional drag for the nanofluid as that of base fluid. Moreover, the particle-particle, particle-wall, and particle-fluid interaction is less as the volume fraction of nanofluids is less than 1%. The results obtained from the present study are consistent with the study of Koo and Kleinstreuer [8] who concluded that particle interaction is less for nanofluids having volume fraction less than 0.5%, and particle interaction is profound for volume fraction more than 1%. This is the reason that pressure drop for all nanofluids is negligibly small.

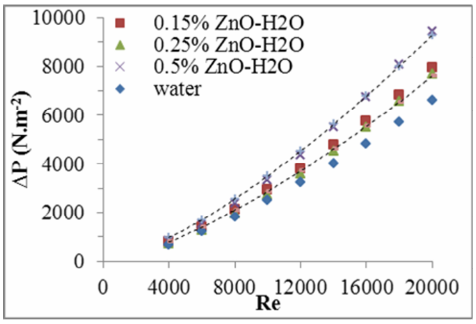


Fig. 10. Graph of Re verses ΔP plotted from Equation of best fitted curves for ZnO-H_2O.

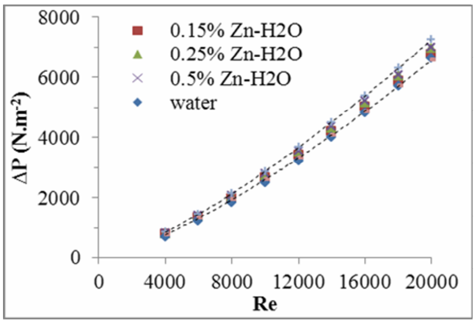


Fig. 11. Graph of Re verses ΔP plotted from Equation of best fitted curves for Zn-H_2O.

4.3 Evaluation of heat transfer performance for nanofluids

We can conclude from our study of the nanofluids in the preceding sections, that enhancement in h and ΔP increases with increase in Reynolds number for all the nanofluids of different volume fractions and at the same time pressure drop also increases. Due to replacement of conventional fluids by nanofluids in heat transfer applications, heat transfer increases, but the pumping power also increases. A performance evaluation criteria (PEC) is required to make an overall conclusion about energy efficiency of nanofluids compared to water. Sébastien et al. [6] defined PEC based on energy global approach. PEC is the ratio of heat flow rate transferred to the required pumping power in the test section.

$$PEC = \frac{m.Cp\left(T_0 - T_i\right)}{v.\Delta P} \quad \text{(Where, } v \text{ is discharge in m}^3\text{.sec}^{-1}\text{)}\ .$$

This criterion directly relates to the gains and losses of energy in an industrial plant. The PEC is determined for all the nanofluids considered for the present study. The graph of enhancement in PEC is plotted against Re and the same is presented in Fig. 12. We can observe from the graph, that 0.5% Zn-H_2O nanofluid has the highest enhancement in PEC indicating high performing fluid. In addition, to having a clear understanding about enhancement in h and enhancement in ΔP for 0.5% Zn-H_2O nanofluid, the graph of hnf/hw and Δpnf/Δpw is also plotted and presented in Fig. 13.

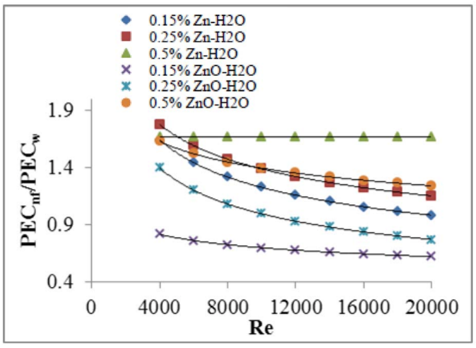


Fig. 12. Ratio of PEC versus Re for all nanofluids under study.

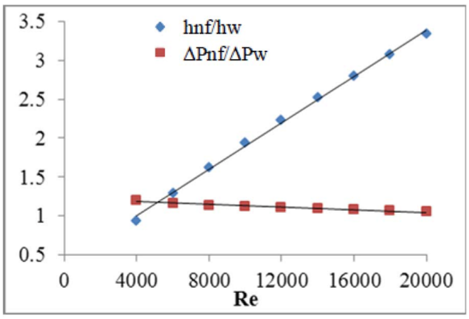


Fig. 13. Enhancement in h and ΔP versus Re for 0.5% Zn-H_2O nanofluid.

4.4 Assessment of benefits for use of nanofluid in automobile radiato

Amongst all the nanofluids under consideration, 0.5% Zn-H_2O proved to be a high performing fluid. Hence, we shall now consider the benefits when the nanofluid in automobile radiator of ECS replaces water. In ECS, higher heat rejection to coolant will reduce the thermal efficiency of the engine, and lower heat rejection will cause overheating of the engine. Hence, to assess the performance of nanofluid in automobile radiator, the following benefit evaluation criteria (BEC) is suitable.

For the same heat transfer, temperature difference, and Reynolds number, determination of reduction in area, pumping power, and inventory of the coolant if the nanofluid replaces the water in the heat exchanger.

We shall now derive the required heat transfer relations for assessment of benefits as per BEC -

For the same heat transfer to nanofluid and water

$$q = h_w A_w \Delta T_{LMTDw} = h_{nf} A_{nf} \Delta T_{LMTDnf} .$$

However, for the same temperature difference:

$$\Delta T_{LMTDw} = \Delta T_{LMTDnf} .$$

Combining above two relations $A_{nf} = \frac{h_w}{h_{nf}} A_w$.

As heat transferred is equal to heat flow rate for both fluids

$$m_w Cp_w \left(To_w - Ti_w \right) = m_{nf} Cp_{nf} \left(To_{nf} - Ti_{nf} \right) .$$

For the same temperature difference, the above equation becomes

$$m_w Cp_w = m_{nf} Cp_{nf} , \quad \frac{m_w}{m_{nf}} = \frac{Cp_{nf}}{Cp_w} .$$

Pumping power (P) required is

$$P_w = \frac{m_w}{\rho_w} \Delta P_w ,$$

$$P_{nf} = \frac{m_{nf}}{\rho_{nf}} \Delta P_{nf} ,$$

$$\frac{P_w}{P_{nf}} = \frac{m_w}{m_{nf}} \frac{\rho_{nf}}{\rho_w} \frac{\Delta P_w}{\Delta P_{nf}} .$$

For same Reynolds number

$$\frac{4 m_w}{\pi D \mu_w} = \frac{4 m_{nf}}{\pi D \mu_{nf}} ,$$

$$\frac{m_w}{m_{nf}} = \frac{\mu_w}{\mu_{nf}} .$$

Combining the above two relations

$$\frac{P_w}{P_{nf}} = \frac{\mu_w}{\mu_{nf}} \frac{\rho_{nf}}{\rho_w} \frac{\Delta P_w}{\Delta P_{nf}} ,$$

$$P_{nf} = \frac{\mu_{nf}}{\mu_w} \frac{\rho_w}{\rho_{nf}} \frac{\Delta P_w}{\Delta P_{nf}} P_w .$$

Inventory of the fluid (v) is

$$\vartheta_w = \frac{\pi}{4} D_w^{\,2} L ,$$

$$\vartheta_{nf} = \frac{\pi}{4} D_{nf}^{\,2} L .$$

Taking ratio of above equations

$$\frac{\vartheta_w}{\vartheta_{nf}} = \left(\frac{D_w}{D_{nf}} \right)^2 ,$$

$$\frac{\vartheta_w}{\vartheta_{nf}} = \left(\frac{A_w}{A_{nf}} \right)^2 .$$

Inventory of the fluids in terms of heat transfer enhancement will become

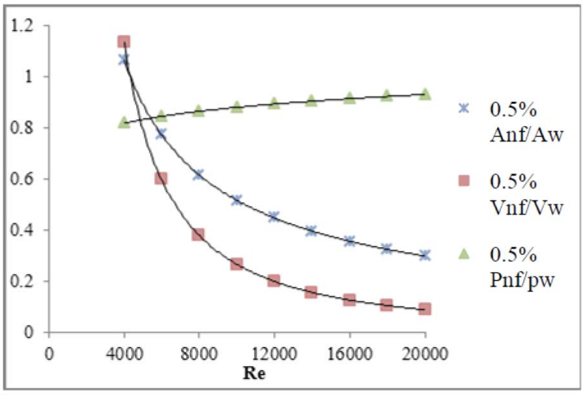


Fig. 14. Variation of reduction in surface area, inventory of the fluid, pumping power as per Re when 0.5% Zn-H_2O nanofluid replaces the water in an automobile radiator.

$$\frac{\vartheta_w}{\vartheta_{nf}} = \left(\frac{h_{nf}}{h_w}\right)^2, \quad \vartheta_{nf} = \left(\frac{h_w}{h_{nf}}\right)^2 \vartheta_w .$$

Finally, following relations achieved as per BEC

$$A_{nf} = \frac{h_w}{h_{nf}} A_w \tag{14}$$

$$P_{nf} = \frac{\mu_{nf}}{\mu_w} \frac{\rho_w}{\rho_{nf}} \frac{\Delta P_w}{\Delta P_{nf}} P_w \tag{15}$$

$$\vartheta_{nf} = \left(\frac{h_w}{h_{nf}}\right)^2 \vartheta_w . \tag{16}$$

For a fixed Reynolds number, with the above equations (Eqs. (14)-(16)), and the experimentally estimated value of h_{nf} / h_w and $\Delta P_{nf} / \Delta P_w$ from the equation of best curve for 0.5% Zn-H_2O nanofluid, the area ratio = A_{nf}/A_w, pumping power ratio = P_{nf}/P_w, inventory of the fluid ratio = v_{nf} / v_w are estimated. The graphs of all the ratios versus Reynolds number is presented in Fig. 14. From the graph and best fitted equation by regression analysis, for the automobile radiator, it can be concluded that heat transfer area reduces as per Eq. (17), pumping power reduces as per Eq. (18), and inventory of the fluid reduces as per Eq. (19).

$$\frac{A_{nf}}{A_w} = 733.3 Re^{0.78} \tag{17}$$

$$\frac{P_{nf}}{P_w} = 0.420 Re^{0.08} \tag{18}$$

$$\frac{v_{nf}}{v_w} = 53777 Re^{-1.57} . \tag{19}$$

Esmaeili Sany et al. [17] observed Reynolds number of flow in a radiator of 4 stroke 1300 CC car engine as a 6000, when a car is running at 55 Km/hr. If water is replaced by 0.5% Zn-H_2O nanofluid in such a engine cooling system then surface area of the radiator reduces by 24%, inventory of the fluid reduces by 40%, and pumping power reduces by 16% making engine cooling system compact.

5. Conclusions

Zn-H_2O and ZnO-H_2O nanofluid's synthesis involves the one- step method and two- step method, respectively. The characterization indicated nanoparticle size of 41 nm for Zn and 32 nm for ZnO nanoparticles. The studies of the heat transfer and pressure drop characteristics of both nanofluids have been experimentally proven. Three volume fractions (0.15%, 0.25%, 0.5%.) of both nanofluids are taken in to consideration for the study. We have estimated the enhancement of the heat transfer coefficient and pressure drop from experimental observations at constant wall temperature condition when heating the fluid for turbulent flow regime of Reynolds number range 4000 to 20000. The application of performance evaluation criteria proved that 0.5% Zn-H_2O nanofluid has the best heat transfer performance amongst considered nanofluids. Hence, we are taking into consideration 0.5% Zn-H_2O nanofluid to assess the benefits of its use in an automobile radiator. Theoretically, we can derive the relations required for assessment of benefits. The heat transfer surface area and inventory of the coolant for the automobile radiator reduces considerably, and the reduction increases with increase in Reynolds number. While the reduction in pumping power is very small, it increases with Reynolds number slightly. Based on the following relations, it can be concluded that 0.5% Zn-H_2O nanofluid is an energy efficient fluid compared to water for the automobile radiator.

$$\frac{A_{nf}}{A_w} = 733.3 Re^{0.78} ,$$

$$\frac{P_{nf}}{P_w} = 0.420 Re^{0.08} ,$$

$$\frac{v_{nf}}{v_w} = 53777 Re^{-1.57} .$$

Acknowledgment

This work is supported by Nagesh Karajagi Orchid College of Engg. And Tech., Solapur-413005, Maharashtra, India.

Nomenclature

ΔP : Pressure drop ($N.m^{-2}$)
ΔT : Temperature difference (K)
A_s : Area (m^2)
C_p : Specific Heat ($J.kg^{-1}. K^{-1}$)
K : Thermal conductivity ($W.m^{-1}. K^{-1}$)
m : Mass flow rate ($Kg\ sec^{-1}$)

P : Pumping power (Watt)
Re : Reynolds number
T : Temperature (K)
v : Inventory of the fluid (m^{-3})
μ : Dynamic viscosity (pa.s)
ρ : Density ($kg.m^{-3}$)
φ : Volume fraction of nanoparticles in nanofluid

Subscripts

LMTD : Logarithmic mean temperature difference
nf : Nanofluid
s : Surface
o : Outer
i : Inner
w : Water

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