Grenze International Journal of Engineering and Technology, Jan Issue

Performance Analysis of Wickless Heat Pipe Heat Exchanger using Water based Copper Nanofluid

Yogita Umesh Yerne[1] and Siddappa Sharanappa Bhusnoor[2]
[1]Research Scholar, Department of Mechanical Engineering, K. J. Somaiya College of Engineering, Vidyavihar, Mumbai-400077, India.
Email: yogotayerne@ somaiya.edu
[2]Professor, Department of Mechanical Engineering, K. J. Somaiya College of Engineering, Somaiya Vidyavihar University, Mumbai - 400077, India.
Email: siddappabhusnoor@somaiya.edu

***Abstract*—Present study focuses on recovery of heat from waste gas at a simulated engine exhaust conditions using wickless heat pipe heat exchanger (WHPHE). WHPHE is constructed using copper tube of 12 mm internal diameter and 2 mm thickness with evaporator and condenser sections of length 150 mm each and a central adiabatic section of length 50 mm. Bench scale experimental setup was developed to analyze the thermal performance of WHPHE at various hot gas inlet temperature (~134, 205 and 280 °C) and flow rates (Re 2500 to 4000 in a step of 500) using cold fluid as air at different flow rates (12, 18, 24 and 30 lpm) and inlet average temperature of 32 °C at atmospheric pressure. Initially De-Ionized (DI) water is used as a working fluid and in the second stage, nanofluid of Copper/De-Ionized water (Cu-DI water) is used as a working fluid at various concentrations (50, 100, 150, 200 ppm) for all experimental conditions.**

Theoretical analysis of wickless heat pipe heat exchanger is carried out using Ɛ-NTU method to predict the performance parameters using DI water as a working fluid. Comparison of experimental results using DI water as a working fluid with theoretical predictions shows that theoretical analysis under predicts the experimental results by 5 to 18.8% for majority of the experimental conditions and over predicts by 1.5 to 18% for few of the conditions. Experimental results of performance parameters of wickless heat pipe heat exchanger using DI water as a working fluid are compared with that of using Cu/DI water nanofluid. From the experimental data it was observed that effectiveness, overall heat transfer coefficient and rate of heat recovery using Cu-DI nanofluid (150 ppm) are 22%, 45% and 34 % more than that of using DI water as a working fluid respectively. Hence it is concluded that Cu-DI nanofluid of150 ppm is the optimum concentration for the maximum rate of heat recovery from the hot gas at a simulated engine conditions

***Index Terms*— Engine exhaust, nanofluid, effectiveness, DI water, waste heat, heat recovery, heat transfer coefficient, Thermal conductivity, viscosity, density, and Thermal resistance.**

I. INTRODUCTION

In the current status of the world due to the increase in energy requirement for the different processing industries, such as steel plant, power plant as well as transportation, the use of fossil fuel is increased. Among all these

Grenze ID: 01.GIJET.7.1.20

sources diesel engines have a wide field of applications due to their higher efficiency. Despite of higher efficiency, a significant amount of input heat energy (30-40%) is expelled into the environment through the exhaust of a diesel engine [1]. Among the different methods used to recover the heat from the engine exhaust, use of heat exchanger is more popular [2]. Among all, the heat pipe heat exchanger is observed to be more efficient device to recover heat energy from the waste heat [3]. Theoretical thermal analysis of heat recovery by two phase closed Thermosyphon from engine exhaust is presented by Yerne and Bhusnoor[4].There are very limited studies for recovery of waste heat from the engine exhaust by using wickless heat pipe heat exchanger (Thermosyphon) and nanofluid as a working fluid [5]. In the literature most of the study is observed for the non metal nanoparticle with the water as the base fluid and the operating temperature range is below ~100 C. But there is limited study on the use of metallic nanofluid at higher operating temperature range over 100 C. In various fields and appliances heat pipe heat exchanger can be used due to its high heat transport capacity. Thermal properties of working fluid plays an important role in the performance of heat pipe heat exchanger, hence it is necessary to improve the thermal properties of working fluids by adding metallic or non-metallic nanoparticles to the base fluids [6].

Yang et al. [7] investigated an open loop wickless heat pipe heat exchanger by using CuO nanoparticles in the base fluid water with mass concentrations of nanoparticles varied in the range of 0.1% to 1.5% wt. They observed that boiling heat transfer rate was improves in evaporator by addition of nano particles, they also observed that the optimal value of concentration of 1% by wt. of Nanoparticle is more effective [8]. From the literature it is evident that from the automobiles more than 25-30% of total energy discharges into the environment in the form of waste heat which causes the loss of energy and also affect on health and environment. And there is no considerable work is done in heat recovery by using heat pipe heat exchanger from the engine exhaust. From the literature study, it is observed that there is no previous work on the wickless heat pipe heat exchanger with the working fluid as a Cu/DI water nanofluid operating at temperature above 100 ^{0}C. Hence the focus of present study is to analyze the performance of wickless heat pipe heat exchanger using working fluid as DI water and Cu/DI water nanofluid with the different concentration (50, 100, 150 and 200 ppm) at simulated engine exhaust conditions (temperature range of 134, 205 and 280 ^{0}C and Flow Re of 2500 to 4000).

II. MATERIALS AND METHODS

Initially theoretical design analysis of wickless heat pipe heat exchanger was carried out using DI water and CU/DI water at various concentrations at simulated engine conditions. In the second stage a bench scale setup was developed to study the various performance parameters of the wickless heat pipe heat exchanger (with DI water and CU/DI water as a working fluid) at various hot gas flow rate, inlet temperatures typical of engine exhaust conditions using atmospheric air as a cooling media at various flow rates. Details of the Materials and methods used in this study are explained in below sub sections.

A. Thermal Analysis of Wickless Heat Pipe Heat Exchanger

For the thermal analysis of heat pipe heat exchanger Ɛ-NTU method developed by Kays and London[9] is used, which can be expressed as;

For Evaporator Section

$$\varepsilon_e = 1 - \exp(-NTU)_e --- (1)$$

For Condenser Section

$$\varepsilon_c = 1 - \exp(-NTU)_c --- (2)$$

Number of transfer units (NTU) for the evaporator and condenser sections can be expressed as;

$$(NTU)_e = \frac{(UA)_e}{C_e} --- (3)$$

$$(NTU)_c = \frac{(UA)_c}{C_c} --- (4)$$

The overall effectiveness of the heat exchanger ε_t is expressed as

If, $C_h > C_c$; $$\varepsilon_t = \left(\frac{1}{\varepsilon_c} + \frac{\frac{C_c}{C_h}}{\varepsilon_e}\right)^{-1} --- (5)$$

If, $C_c > C_h$; $$\varepsilon_t = \left(\frac{1}{\varepsilon_e} + \frac{C_h/C_c}{\varepsilon_c}\right)^{-1} --- (6)$$

Calculation for Outer Heat Transfer Coefficient of Single Tube Heat Pipe Heat Exchanger:

If D_h is the hydraulic diameter of annulus region, V_h is the velocity of shell side fluid for the given mass flow rate and geometry, then gas Reynolds number can be expressed as;

$$Re_h = \frac{\rho_h D_h v_h}{\mu_h} ---(7)$$

$$V_h = \frac{\dot{m}_h}{A_c \rho_h} ---(8)$$

$$A_c = \frac{\pi}{4}(D_i^{2} - d_o^{2}) ---(9)$$

$$D_h = D_i - d_o ---(10)$$

For external cross flow over a single cylinder, Nusselt correlation can be expressed as [10];

$$Nu_o = CRe^m Pr^{0.37}(Pr/Pr_w)^{0.25} = h_o D_e/k ---(11)$$

The constants C and m are depends on Re as given in below Table 1 [**Error! Bookmark not defined.**]. For the given geometry and mass flow rate in the outer shell, the shell side heat transfer coefficient can be expressed as;

$$h_o = \frac{Nu_o k}{D_e} ---(12)$$

TABLE I. CONSTANTS OF EQ. (14) FOR A CIRCULAR CYLINDER IN CROSS FLOW [**ERROR! BOOKMARK NOT DEFINED.**]

Re	C	m
40–1000	0.51	0.5
10^3–2 x 10^5	0.26	0.6

B. Modeling of Thermo physical Properties of working fluid and Performance Parameters of Heat Exchanger

In this study we have derived a theoretical model from the basic equations available in literature [11] for analyzing Thermo physical Properties of working fluid and Performance Parameters of HPHE.

Thermal Conductivity: The effective thermal conductivity of nanofluid can be calculated by using following expression proposed by Jang and Choi[12].

$$K_{nf} = K_f(1-\phi) + K_p\phi + 3\frac{d_f}{d_p}K_f\phi Re_{dp}^{2}\ Pr ---(13)$$

*Density of the Nanofluid***:** Density of nanofluid can be determined by using the following expression [13]

$$\rho_{nf} = \phi\rho_p + (1-\phi)\rho_f ---(14)$$

Where $\rho_{nf,}$ ρ_p and ρ_f are the densities of the nanofluid, nanoparticles, and base fluid, respectively.

Specific Heat of nanofluid: Specific heat of nanofluid can be determined by using following expression[14]

$$C_{pnf} = \phi C_{pp} + (1-\phi)C_{pf} ---(15)$$

Where $C_{pnf,}$ C_{pp} and C_{pf} are the specific heat of the nanofluid, nanoparticles, and base fluid, respectively.

*Viscosity of Nanofluid***:** Viscosity of Nanofluid is an important parameter for various practical applications due its direct effect on the pressure drop in forced convection flow problems. Dynamic viscosity of dilute suspensions that contain spherical particles has been expresses as [15];

$$\mu_{nf} = (1 + 2.5\phi)\mu_f ---(16)$$

C. Analysis of Convective Heat Transfer coefficient of base fluid (hf) and nanofluid (hnf)

Heat transfer performance of nanofluids can be analyzed by using classical correlations developed for the Nusselt number for the flow of pure fluids.

Boiling heat transfer coefficient of base fluid (hfei)

In the present study Imura's correlation is used the determination of the average Nusselt number. This correlation covers natural convection, combined convection and nucleate boiling which can be expressed as,

$$h_{fei} = 0.32\ \frac{\rho_f^{0.65}k_f^{0.3}Cp_f^{0.7}g^{0.2}q_e^{0.4}}{\rho_v^{0.25}h_{fg}^{0.4}\mu_f^{0.1}}\left(\frac{P_{sat}}{P_{atm}}\right) ---(17)$$

Condensation heat transfer coefficient of base fluid (hfci)

In the condenser assuming all the mass flowing as liquid, the Heat transfer Coefficient h_L can be expressed by the Dittus-Boelter equation as:

$$h_L = 0.023\ Re^{0.8}Pr^{0.4}\frac{k_f}{D_o} ---(18)$$

And mean heat transfer coefficient for condensation can be find out by Shah M. [16]

$$h_{fci} = h_L\left(0.55 + \frac{2.09}{Pr^{0.4}}\right) --- (19)$$

The basis of single phase model proposed by Xuan and Roetzel[] is the fact that solid particles in nanofluid are ultrafine (<100 nm) and are easily fluidized. The equation for heat transfer coefficient of nanofluid can be expressed as;

$$h_{nfei} = 0.32\,\frac{\rho_{nf}^{0.65}K_{nf}^{0.3}Cp_{nf}^{0.7}g^{0.2}q_e^{0.4}}{\rho_v^{0.25}h_{fg}^{0.4}\mu_{nf}^{0.1}}\left(\frac{Psat}{Patm}\right) --- (20)$$

Dividing Eq. 20 by Eq. 17, we obtain the ratio of nanofluid heat transfer coefficient as;

$$\frac{h_{nfei}}{h_{fei}} = \left(\frac{\rho_{nf}}{\rho_f}\right)^{0.65}\left(\frac{Cp_{nf}}{Cp_f}\right)^{0.7}\left(\frac{k_{nf}}{k_f}\right)^{0.3} --- (21)$$

ratio of heat transfer coefficients of Nano fluid to base fluid in the condenser can be expressed as;

$$\frac{h_{nfci}}{h_{fci}} = \left(\frac{Re_{nf}}{Re_f}\right)^{0.8}\left(\frac{Pr_{nf}}{Pr_f}\right)^{0.4}\left(\frac{k_{nf}}{k_f}\right)\left(\frac{0.55Pr_{nf}^{0.4} + 2.05}{Pr_{nf}^{0.4}}\right)\left(\frac{Pr_f^{0.4}}{0.55Pr_f^{0.4} + 2.05}\right) --- (22)$$

D. Overall heat transfer coefficient on shell side of evaporator (Uoe) and condenser (Uoc)

The overall heat transfer coefficient on shell side of evaporator (U_{oe}) and condenser (U_{oc}) by considering outer heat transfer area can be expresses as;

$$U_{oe} = \frac{1}{h_{oe}} + \frac{A_{oe}}{A_{ie}h_{ie}} ---(25)$$

$$U_{oc} = \frac{1}{h_{oc}} + \frac{A_{oc}}{A_{ic}h_{ic}} ---(26)$$

E. Experimental method to find effectiveness of Heat Pipe Heat Exchanger

The effectiveness of thermosyphon can be defined as the ratio of heat transfer rate of heat exchange to the maximum possible heat transfer rate between the air streams

$$\varepsilon_t = \frac{q_{actual}}{q_{max}} --- (27)$$

If $C_h > C_c$

$$\varepsilon_t = \frac{T_{c,out} - T_{c,in}}{T_{h,in} - T_{c,in}} --- (28)$$

If $C_h < C_c$

$$\varepsilon_t = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} --- (29)$$

III. Development of Bench Scale Experimental Setup

The design of the experimental setup is intended to study the heat recovery from engine exhaust by using wickless heat pipe heat exchanger with working fluid as DI water and Cu/DI water. Further, it is also intended to fulfil the requirements of experimental validation of the theoretical analysis for the heat recovery with maximum accuracy. The heat pipe heat exchanger theoretically analysed and designed by Yogita and Bhusnoor (2019) is fabricated using copper tube of 12 mm internal diameter and 2 mm thickness with evaporator and condenser sections of length 150 mm each and a central adiabatic section of length 50 mm. Figure 1 shows the photograph of bench scale experimental setup developed in this study. The experimental matrix for the study is presented in the Table II.

TABLE II. Experimental Conditions for Bench Scale Setup

Parameter	Bench scale set up
Hot fluid and Cold fluid	Air
Inlet Temperatures of hot fluid (°C)	134, 205 and 280
Cold fluid inlet Temperatures (°C)	Air at atmospheric temperature (32°)
Re of hot fluid	2500, 3000, 3500, 4000
Mass flow rate of cold fluid (lpm)	12,18, 24, 30
Thermosyphon dimensions (Material)	12 mm ID, 2mm thickness, length 350 mm (Copper, k_t=400 W/mK)
Working Fluids	DI Water , Cu/DI water Nanofluid (50, 100 , 150 and 200 ppm)
Working Fluids	DI Water , Cu/DI water Nanofluid (50, 100 , 150 and 200 ppm)

The compressed air from compressor is divided into two steams, one stream is passed to the heater to supply hot to evaporator section and stream of cold air is supplied to the condenser section through the rotameter. Temperatures at various points of the evaporator are measured by Cr-Al thermocouple wires. In this study performance parameters of wickless heat pipe heat exchanger at various experimental conditions are analyzed using DI Water and Cu/DI water Nanofluid at various concentrations of Cu nanoparticles in the base fluid, and experimental results are compared with theoretical predictions of DI water.

IV. Results and Discussion

Theoretical and experimental results obtained as per the experimental matrix are discussed in this section.

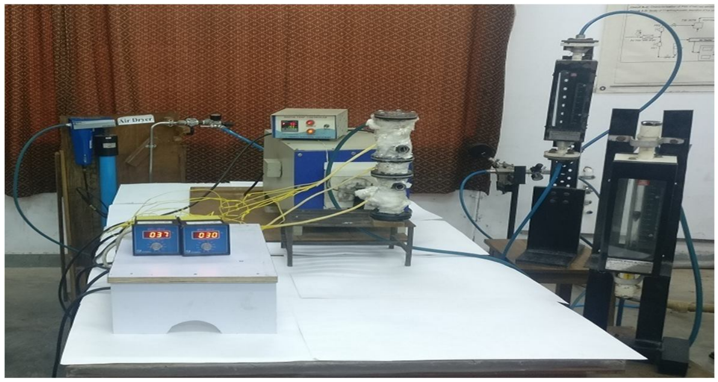

Figure 1 Photograph of Bench scale Experimental setup for Performance analysis of wickless heat pipe heat exchanger

A. Effect of Mass Flow Rate of Hot Gas on Boiling Heat Transfer Coefficient of Nanofluid

Figure 2 shows effect of nanofluid concentration on the boiling heat transfer coefficient at various hot gas flow rate. The boiling heat transfer coefficient increases with the increase of concentration from 50 to 150 ppm at given temperature and with increase in flow rate. Comparison of experimental results using working fluid as Cu/DI water nanofluid (150 ppm) with that DI water shows, that there is ~ 30.7% increase in boiling heat transfer using Nanofluid as working fluid. From Fig. 2 it is also observed that the theoretical values of boiling heat transfer coefficient are under predicted compare to experimental results by maximum ~20%.

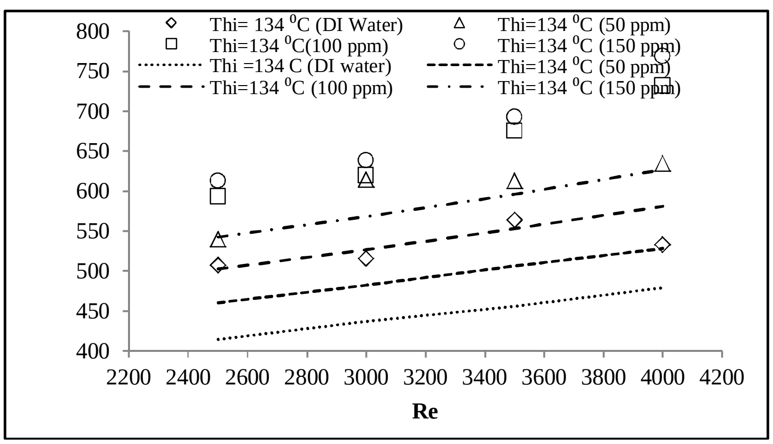

Figure 2 Effect of hot gas flow rate on boiling heat transfer coefficient of DI water and nano fluid with different concentration

B. Effect of Hot gas flow rate on effectiveness of wickless heat pipe heat exchanger

Influence of nanofluid concentration on the effectiveness of heat pipe heat exchanger at various hot gas flow rate and gas inlet temperature are plotted in Figure 3 along with theoretical predictions using DI water for comparison. From the Figure 3, it is noticed that the effectiveness of wickless heat pipe heat exchanger for all nanofluid concentration increases with increase in the hot gas flow rate at fixed gas inlet temperature. It is also observed that for increase in gas inlet temperature from 134 and 280 ^{0}C at any hot gas flow rate there is increase in effectiveness due to increase in concentration. For 150 ppm concentration of nanofluid there is up to 23.5% increase in effectiveness is observed where as by further increase in concentration to 200 ppm there is drop of effectiveness by 5 % due to increase in viscosity because of the reduction in convection heat transfer rate of the nanofluid.

C. Effect of Hot Gas Flow Rate on Evaporator Overall Heat Transfer Coefficient (Uoe)

Influence of nanofluid concentration on the evaporator overall heat transfer of heat pipe heat exchanger at various hot gas flow rate and gas inlet temperature are plotted in Figure 4 along with theoretical predictions using DI water for comparison. From the Figure 4 it is observed that with the increase in hot gas mass flow rate there is increase in overall heat transfer coefficient at all gas inlet temperature and it increases with increase in concentration and temperature at given flow rate. It is observed that due to increase in concentration of nanoparticle from 50 to 150 ppm the overall heat transfer coefficient increased to 44.56 %, as compare to DI water.

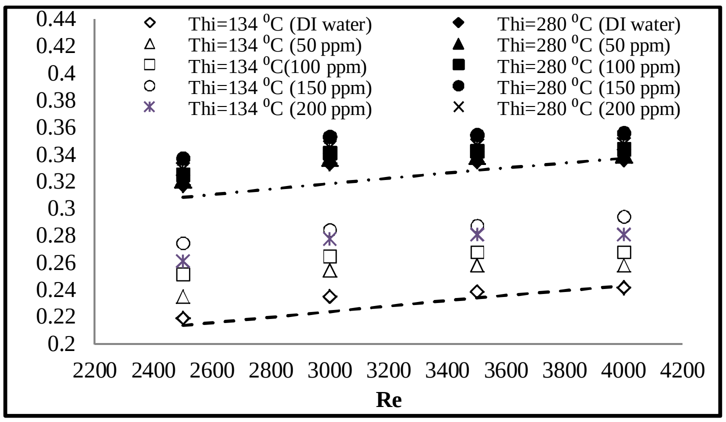

Figure 3 Effect of Hot gas flow rate on effectiveness of the wickless heat pipe heat exchanger at various nanofluid concentration and cold fluid mass flow rate of 30 lpm and at two different gas inlet temperature 134 and 280 ^{0}C

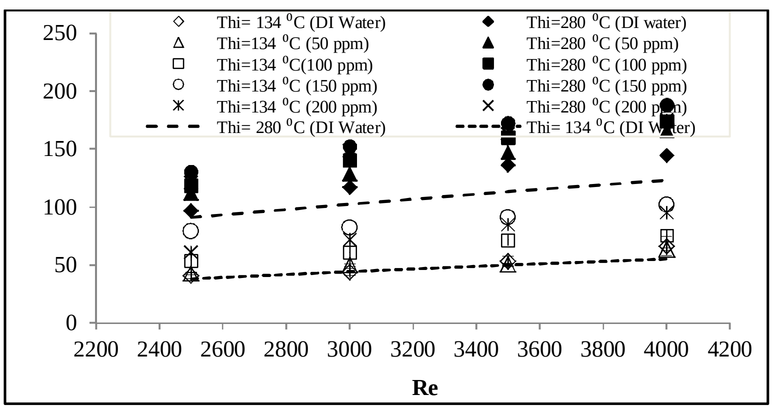

Figure 4 Effect of hot fluid mass flow rate overall heat transfer coefficient at various nanofluid concentration and cold fluid flow rate of 12lpm and at hot gas inlet temperature of 134 and 280 ^{0}C

D. Effect of Hot Gas Flow Rate on Effective Thermal Conductivity of Wickless Heat Pipe Heat Exchanger

Influence of nanofluid concentration on the Effective thermal conductivity of heat pipe heat exchanger at various hot gas flow rate and gas inlet temperature are plotted in Figure 5 along with theoretical predictions using DI water for comparison. From the Fig.5 it is observed that with the increase in hot gas fluid mass flow rate there is increase effective thermal conductivity at all gas inlet temperature. For all Nanofluid Concentration (DI water, 50,100,150 and 200 ppm) the effective thermal conductivity was in the range of 5000 to 12000 W/mK at hot gas temperature of 280 ^{0}C, whereas for 134 ^{0}C it is in the range of 400 to 2600 W/mK. At higher temperature the thermal resistance of the fluid and solid decreases, this results in increase in effective thermal conductivity. From Fig.5 it is also observed that due to increase in concentration of the nanofluid from 50 to 150 ppm there is increase in effective thermal conductivity where as further increase in concentration to 200 ppm the effective conductivity reduces by around 3 %.

E. Effect of Hot Gas Flow Rate on Heat Recovery of Wickless Heat Pipe Heat Exchanger

Influence of nanofluid concentration on the rate of heat recovered from the heat pipe heat exchanger at various hot gas flow rate and gas inlet temperature are plotted in Figure 6 along with theoretical predictions using DI water for comparison.

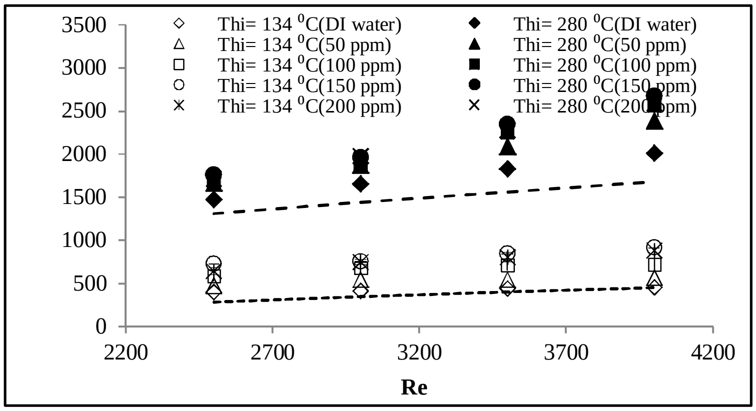

Figure 5 Effect of hot fluid mass flow rate on Effective thermal conductivity of the heat pipe heat exchanger at various nanofluid concentration and cold fluid flow rate of 18lpm and at two different gas inlet temperatures134, 280 ^{0}C

From the Fig.6 it is observed that with the increase in evaporator side fluid mass flow rate there is increase heat recovery rate at all gas inlet temperature due to more heat potential. with the working fluid of 150 ppm the heat recovery rate is observed to be increase up to 11 % and 26% for the 280 ⁰C and 134 ⁰C respectively as compare to DI water. But for further increase in concentration of nanoparticle to 200 ppm there is drop of rate heat recovery observed compared to 150 ppm nanofluid up to 12 % due to drop in overall heat transfer coefficient and effective thermal conductivity of wickless heat pipe heat exchanger.

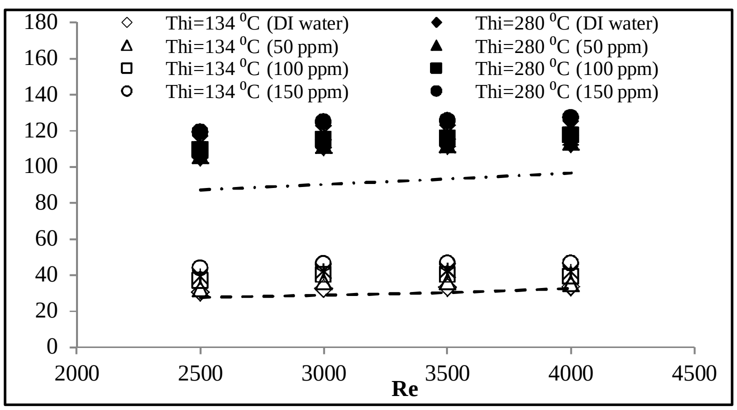

Figure 6 Effect of hot fluid mass flow rate on heat recovery by the heat pipe heat exchanger at various nanofluid concentration and cold fluid flow rate of 30lpm and at hot gas inlet temperature of 134 and 280 ^{0}C

V. CONCLUSIONS

A summary of experimental analysis drawn on the basis of present work are summarized here.

1. Effectiveness of heat exchanger increases with the increase in concentration of nanofluid due to increase in thermal conductivity. For 150 ppm maximum 22% increment in effectiveness is observed but for the nanofluid concentration of 200 ppm the effectiveness is 6% less than that of 150 ppm.
2. Experimental results are higher than the theoretical predictions in the range of 5 to 18.8 % for entire range of the experimental conditions.

3. The thermal resistance of wickless heat pipe heat exchanger decreases with the increase in concentration of nanofluid from 50 to 150 ppm due to increase in its thermal conductivity.
4. The maximum reduction in thermals resistance is observed for 150 ppm concentration nanofluid (which is around 55%), as Compare DI water. But for 200 ppm nanofluid concentration there is increase in thermal resistance of 9% as compare to 150 ppm due to the increase in viscosity of the working fluid.
5. There is 34 % increase in rate of heat recovery is observed with the increase in nanofluid concentration to 150 ppm as compared to DI water. Further increase in concentration to 200 ppm there is decrease in rate of heat recovery of 5%, which is due increase in thermal resistance of the heat exchanger.
6. From the results it is clear that the effectiveness of the heat exchanger is highest at 150 ppm nanofluid concentration for all the temperature range and mass flow rate of cold fluid.

ACKNOWLEDGMENT

The work described in this paper was conducted in the Internal Combustion Engine Laboratory of K. J. Somaiya College of Engineering, Mumbai- 400 077. We would like to thank Somaiya Trust Vidyavihar, Mumbai, India and Principal of K. J. Somaiya College of Engineering (KJSCE) for financial support for the development of bench scale setup at KJSCE. The first author would like to thank the staff of the Internal Combustion Engine Laboratory and the workshop of KJSCE for their support.

REFERENCES

[1] Pandiyarajan V, Chinna Pandian M, Malan E, Velraj R, Seeniraj RV., Experimental investigation on heat recovery from diesel engine exhaust using finned shell and tube heat exchanger and thermal storage system. Applied Energy, 2011; 88:77–87.

[2] Saidur R, Rezaei M, Muzammil W, Hassan M, Paria S, Hasanuzzaman M. Technologies to recover exhaust heat from internal combustion engines. Renewable and Sustainable Energy Rev, 2012; 16:5649–59.

[3] Yang F, Yuan X, Lin G, Waste heat recovery using heat pipe heat exchanger for heating automobile using exhaust gas, Applied Therm. Eng. 2003; 23:367–372

[4] Yerne Y U, Bhusnoor S S, Theoretical thermal analysis of heat recovery by two phase closed Thermosyphon from engine exhaust, Heat and Mass Transfer, Springer, 2019, 1-11.

[5] Nazari M, Ghasempour R, Ahmadi M, Heydarian G,Shafii M, Experi- mental investigation of graphene oxide nanofluid on heat transfer enhance- ment of pulsating heat pipe, International Communication in Heat Mass Tran. 2018; 91:90-94.

[6] Choi S., Nanofluids: A new fluid of scientific research and innovative applications. Heat Transfer Engineering, 2008; 29:429–431.

[7] Yang X, Liu Z, Flow boiling heat transfer in the evaporator of a loop wickless heat pipe heat exchanger operating with CuO based aqueous nanofluid. International Journal of Heat and Mass Transfer 2012; 55:7375–84.

[8] Moradgholi M, Mostafa S, Farzaneh A. Experimental study of using Al2O3/methanol nanofluid in a two phase closed wickless heat pipe heat exchanger array as a novel photovoltaic/thermal system. Solar Energy 2018; 164:243–50.

[9] Kays W, London A, Compact Heat Exchanger Design, third edition, McGraw-Hill, New York, 1984.

[10] Zhukauskas A, Heat transfer from tubes in cross flow, Advances in Heat Transfer, 1972;8: 93-160.

[11] Kakac, S, Li H, Pramuanjaroenkij A. Heat Exchangers: Selection, Rating, and Thermal Design, second ed. CRC Press, BocaRaton, FL,2002.

[12] Jang SP, Choi SUS: Role of Brownian motion in the enhanced thermal conductivity of nanofluids. Applied Physics Letters, 2004, 84:4316.

[13] Pak B, Cho Y, Hydrodynamic and heat transfer study of dispersed fluids with submicron metallic oxide particles, Experimental Heat Transfer, 1998;11:151–70.

[14] Ghaderian J, Sidik N, Kasaeian A, Ghaderian S, Okhovat A, Pakzadeh A, Samion , Yahya W, Performance of Copper Oxide/distilled water nanofluid in evacuated tube solar collector (ETSC) water heater with internal coil under thermosyphon system circulations, Applied Thermal Engineering ,2017;121:520-536.

[15] Drew D, Passman S, Theory of multi component fluids, Berlin, Springer; 1999.

[16] Shah, M, A general correlation for heat transfer during film condensation inside pipes. International Journal of Heat and Mass Transfer, 1979; 22:547–556.

[17] Xuan Y, Roetzel W, Conceptions for heat transfer correlation of nanofluids, International Journal of Heat and Mass Transfer, 2000; 43: 3701-3707.