EXPERIMENTAL INVESTIGATION ON THERMAL PERFORMANCE OF GRAVITY ASSISTED HEAT PIPE HEAT EXCHANGERS

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***Abstract*— The performance of a gravity assisted heat pipe heat exchangers (HPHX) investigated experimentally. The HPHX consist of evaporator and condenser sections of different lengths and designed with three section ratio 1:3, 1:1 and 3:1 keeping the total length of HPHX 300mm. The heat pipes were fabricated with standard copper tube of inner diameter of 22.5 mm. The distilled water and acetone were used as working fluid with filling ratios of 40% and 80% of evaporator volume. In experiments, the exhausted engine waste heat at full load is used for supplying the heat to the evaporator section. The pongamia biodiesel was used to preheat in condenser section before admission into engine cylinder. The experimental results indicated that the effectiveness of HPHX decreases with the increased section ratio. In addition, the effectiveness of the HPHX obtained from the experiments varied between 0.272 and 0.717. The 80% Acetone charged HPHXs shows better results with reduced thermal resistance and larger heat capacity.**

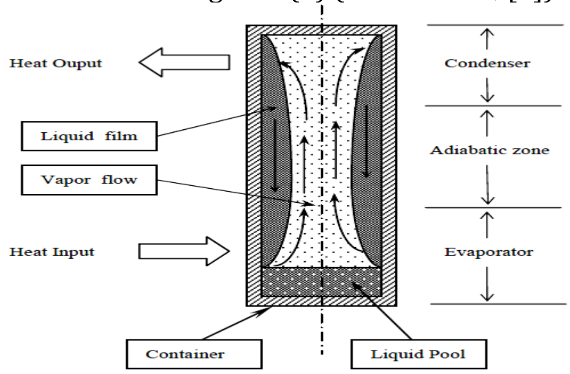
Keywords— Heat Pipe, Heat Exchanger, Preheat, Section Ratio, Filling Ratio.

I. INTRODUCTION

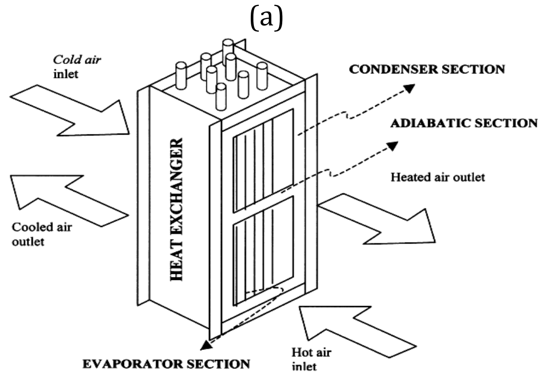
Conventional heat pipe heat exchangers are widely used in waste heat recovery applications. The HPHX comprises of three parts; evaporator, adiabatic and condenser sections. The evaporator section is the part that is always at the bottom due to the condensate returning to this section by gravity force. The simplicity in construction, no wick structure, high effectiveness, high compactness and no cross contamination are the advantages of this recovery device.

The rising energy demands and the continual push to find more energy efficient technologies have been the great reasons for the investigation of waste heat recovery techniques and utilizing biofuels to the maximum extent. Unfortunately, the newer diesel engine designs could not run on biodiesel efficiently, due to much higher viscosity compared to diesel. Many methods have been proposed, including pyrolysis, blending and transesterfication which convert them into esters and use them as a diesel fuel replacement. In the today's and future concerns over the environment and energy security, to bring the biodiesel to the forefront. The preheat of biodiesel using the exhausted engine waste heat is the most suitable and viable solution. The heat pipe application in engine is called as VAPIPE. The heat pipes can be used to vaporize fuel by the exhaust gases before it enters into the engine. The vaporized fuel makes a homogeneous mixture of fuel and air, and improves the combustion (Nag [1]; Arora *et al.*[2]).

Heat pipes are usually a tubular metal structure closed at both ends as shown in Figure 1(a). It encompasses three essential parts: an evaporator, an adiabatic section and a condenser. Inside the heat pipe a working fluid is present both in the liquid and the vapor phases. The heat flux entering the evaporator vaporizes the working fluid, thereby absorbing large quantities of heat. The vapor, travels towards the condenser, propelled by the pressure difference. In the condenser the vapor condenses releasing its latent heat to the heat sink. To complete the cycle, the condensed liquid is pumped back to the evaporator (Luis Santiago, [3]). A thermosyphon heat exchanger (THE) consists of a number of these tubes arranged in rows. they operate with the evaporator section in the high-temperature fluid stream and the condenser section in the low-temperature fluid stream as shown in Figure 1(b) (Noie & Lotfi, [4]).



(a)



(b)

Figure 1: Typical Heat pipe (a) and the heat pipe heat exchanger (b).

Srimuang *et al.* [5] reported the effects of heat pipe thickness, evaporator length, and type and filling ratios of working fluid on performances of the heat pipe heat exchanger (HPHE). Furthermore, they suggested reducing cross-section area of heat pipe. Amatachaya and Srimuang [6] investigated experimentally the thermal performance of HPHE, and compared with the HPHE. Recently, Noie and Majidian [7] designed, constructed and tested HPHE for heat recovery from surgery room in hospitals. In their experiment, the atmospheric air heated by the electric heater of 1500W, and velocity of hot air for across the evaporator section was 2.3 m/s. the maximum effectiveness was 0.16. Lukitubudi et al. [8] designed, constructed and tested the CHPHE for medium temperature (below 300°C) heat recovery in bakeries. They conducted testes, the air velocities were varied from 1.5 to 5 m/s and the heat inputs the evaporator section were varied from 4 to 20 kW and the exhaust gas temperature inlet into the evaporator section were 300 °C. Their results had shown the effectiveness of 0.18 to 0.63. Habeebullah *et al.* [9] reported the heat recovery from the exhaust gas of industrial gas turbine engines by using heat pipe. The exhaust gases blown through the evaporator section at 300 °C and they were able to extract 70 to 93% of recoverable energy from exhaust gases. Riffat and Gan [10] reported the thermal performance of the tree types of heat pipe heat recovery unit for naturally ventilated building. Their results had shown the air velocity had significant influence on the effectiveness of heat recovery. The effectiveness decreased with increasing air velocity, and the effectiveness was affected by the pipe arrangement. Yang *et al.* [11] investigated experimentally and theoretically the HPHE for warm up air in a large bus by heating applying automotive exhaust gas. They studied exhaust gas across the evaporator section at varied temperature between 100 to 300 °C. They reported the maximum effectiveness of 28%. Noie [12] investigated the thermal performance of an air to air thermosyphon heat exchanger. The temperature inputs at the evaporators were from 100 to 250 °C and found the HPHX effectiveness between 0.37 and 0.65.

Zuo and Gunnerson [13] studied the steady state performance of the gravity assisted two phase closed thermosyphon by varying the operating temperatures, geometry, and working fluid inventory. El-Genk and Saber [14] developed a closed two-phase thermosyphon with specified working fluids, initial filling ratio, evaporator length, power input, vapor temperature, and tube diameter. They concluded that tube diameter, evaporator length, and vapor temperature are dominant factors on thermal performance of closed two-phase thermosyphon, rather than condenser or adiabatic section length. The more influence is the evaporator length. Rittidech *et al.*[15] investigated the effect of the evaporator length on the heat transfer rate flux. The experiments were done heat pipes with 2.03 mm. diameter, filling ratio of 50% and vapor temperature of 50 ºC. The evaporator length had been varied by 50, 100 and 150 mm. It was found that decreased evaporator length, increase the heat flux. Hudakorn[16] reported that, the increased evaporator length decreases the critical heat flux for all inclination angles and the critical heat flux increases with an increase in the inner diameter for all inclination angles. They concluded that the geometries of heat pipes influence the critical heat flux. Noie [17] studied the thermal characteristics of a two-phase closed thermosyphon with the working fluid filling charge ratio ranging from 30 to 90% and a variation in length of the evaporator. He found that the length of the evaporator and the filling ratios are intrinsically related to each other. Grooten *et al.* [18] found that the filling ratio not a crucial for heat transfer characteristics of thermosyphons as long as dry-out of the evaporator is avoided. Dry-out of the evaporator does not occur with a filling ratio of 80% acetone.

Donald *et al.* [19] and Chen *et al.*[20] have studied the effect of fill ratio of evaporation, condensation and overall heat transfer coefficient. The fill ratios used in this experiment were 35% to 100% of the evaporator volume for all three different working fluids. Acetone shows the minimum thermal resistances at all heat inputs for all fill ratios. Water and methanol shows almost similar values of thermal resistances. Tenga *et al.* [21] reported that for working fluid fill ratios greater than 85% of evaporator volume, results better in terms of decreased thermal resistance, increased heat transfer coefficient and reduced temperature difference across the evaporator and condenser. Kannan *et al.* [22] reported that the heat transport capability of water is high compared to other working fluids such as ethanol, methanol and acetone at all filling ratios and operating temperatures. Khazaee *et al.* [23] investigated the effect of filling ratio, aspect ratio, heat input and mass flow rate on the heat transfer characteristic with methanol as a working fluid.

As detailed above, it can be concluded that, many parameters affects the performance of HPHX: the geometric characteristics, physical parameters and operational variables. Thermal performance of the HPHX can be represented by the effectiveness, heat capacity, thermal resistance and the heat transfer coefficients of evaporator and condenser sections. The paper presents the effect of section ratio, working fluid and its filling ratio on the thermal performances of HPHX.

II. DESIGN AND DEVELOPMENT OF HPHX

The working fluid and the tube materials were selected based on the working temperature range as per Amir Faghri [24]. In experiments, the waste exhaust of water cooled engine having temperature range of 200- 300 °C (approx...) at full load is used for supplying the heat to the evaporator section of HPHX. Thus distilled water and acetone were selected as working fluids. The compatible material for water is copper, stainless steel, Nickel, Titanium. The individual heat pipes were fabricated first with the aid of design data as shown in Table 1 and then the HPHXs assemblies developed.

Table 1: The geometry and other parameters of wickless heat pipe and HPHX

Type	Vertical bundle, wickless and gravity assisted		
Material	Copper		
Diameter di (mm)	22.5 mm		
Working fluid	Distilled water, Acetone		
Thickness of the heat pipe wall (t)	2.5 mm		
Vacuum inside heat pipe (Pr.)	0.13 bar		
Saturation temperature inside heat pipe (T_{sat})	51°C		
Transverse pitch 'ST' mm	45	45	45
Longitudinal pitch 'SL' mm	45	45	45
Diagonal pitch 'Dp' mm	31.82	31.82	31.82
Lev (mm)	225	150	75
Lco (mm)	75	150	225
Filling Ratio	40% and 80% of the evaporator volume		
Section Ratio Lc/Le	SR_1= 1:3 **(0.33)**	SR_2= 1:1 **(1)**	SR_3=3:1 **(3)**
Aspect Ratio Le/di	AR_1: **10**	AR_1: **6.66**	AR_1: **3.33**

2.1 Heat pipe heat exchanger section ratio and aspect ratio: Section ratio is the length ratio of condenser to evaporator and *aspect ratio* is the ratio of evaporator length to inside tube diameter. Figure 2 shows the three section ratios considered in the present study SR_1, SR_2 and SR_3 (1:3, 1:1 and 3:1). The commercially available standard copper tube of outer diameter of 25 mm has been chosen. Further, the distilled water and acetone were used as working fluid with filling ratios of 40% and 80% of evaporator volume.

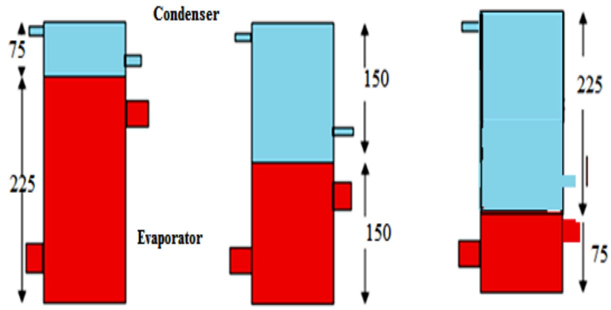


Figure 2: Section ratio of heat pipe heat exchanger 1:3, 1:1 and 3:1

2.2 Assembly of HPHXs : Figure 3 shows the assemblies of HPHXs developed for the three different section ratios SR_1,SR_2 & SR_3 having evaporator lengths 225mm, 150mm & 75mm. These assemblies are then thermally insulated and aluminum claddings were added.

Figure 3: The HPHX assemblies before the thermal insulation and aluminum cladding

Figure 4 shows the heat pipe heat exchanger assembly with the RTD thermocouples connected at the inlet and exit hot fluid (Engine exhaust) and cold fluid (Biodiesel) streams of HPHX. The thermocouples in turn connected to the temperature data logger and communicated to the computer for online data access and storage. The preheated biodiesel is directed to the engine injector through an insulted steel wired pipe to avoid the cooling of biodiesel.

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Figure 4: The Heat pipe heat exchanger assembly

III. EXPERIMENTAL SETUP AND EXPERIMENTATION

Installation and Instrumentation of HPHX Assembly: The assembled heat pipe heat exchanger as shown in the Figure 5 is a bundle of heat pipes installed at the engine exhaust pipe to recover high temperature waste heat from engine exhaust gas. The inlet end of evaporator is connected to the engine exhaust pipe and the other end of evaporator to the surroundings. The fuel supplied to the engine via the condenser sections of HPHXs for preheating.

Figure 5: Installed and instrumented HPHX

The experiments conducted on different modules of HPHXs developed considering the most influencing geometrical, physical and operational parameters. The engine is tested at full engine load and supplied with commercially available pongamia biodiesel that confirms the ASTM standards.

IV. RESULTS AND DISCUSSIONS

Thermal performances of HPHX were represented by effectiveness, heat capacity, thermal resistance and the heat transfer coefficients at evaporator and condenser sections. The effect of section ratio, filling ratio and aspect ratio on the above parameters are discussed here.

4.1 The eff Condenser section ***and filling ratio on effectiveness:*** The effectiveness is defined as the ratio of the actual heat transfer rate of the HPHE to the maximum possible heat transfer rate between the two streams. The experimental results indicated that the effectiveness of HPHXs significantly influenced by section ratio, working fluid and its filling ratio. Figure 6 shows the decreased effectiveness with increased section ratio and decreased aspect ratio irrespective of working fluid and its filling ratio. This is attributed to the larger ind because of the better boilin Evaporator section two-phase liquid moved from the evaporator to the condenser section in faster and effective way. In the experiments the effectiveness varies from 0.272 to 0.717. Further, the acetone charged HPHX with 80 % filling ratio presents the higher effectiveness irrespective of section ratio and aspect ratio. This is due to the higher specific heat capacity of acetone.

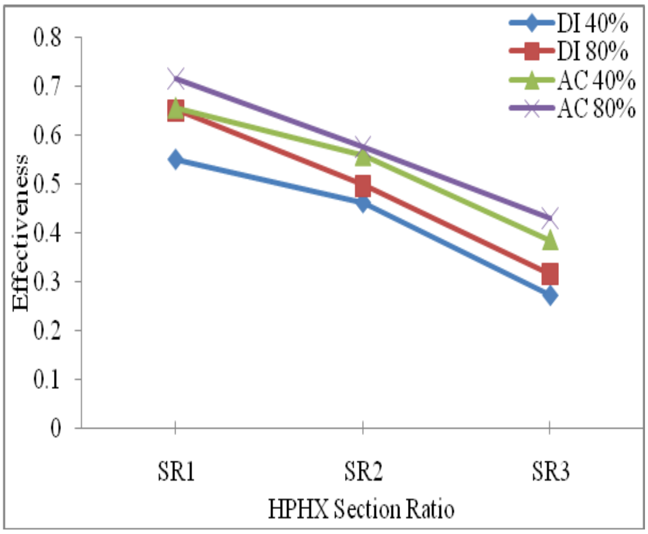

Figure 6: Effect of section ratio and filling ratio of different working fluids on effectiveness

4.2 The effects of section ratio and filling ratio on heat capacity: The results confirmed that the cross sectional area had a relative size to let the bubble vapor move from the evaporator section to the condenser section. Due to this reason the HPHXs with larger evaporator volume transfer higher heat transfer to condenser section and hence the larger recovered heat. It's seen from Figure 7, that the heat capacity decreased with increased section ratio and decreased aspect ratio for both the working fluids irrespective of fluid charge. But the acetone charged HPHXs exhibit the higher heat recovery from engine exhaust for SR_1.

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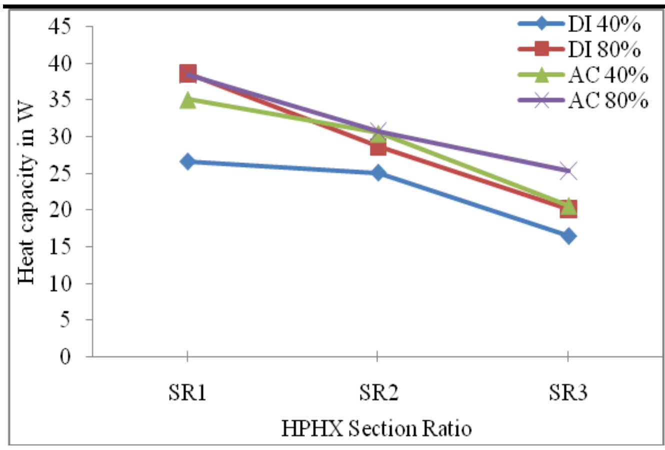

Figure 7: Effect of section ratio and filling ratio of different working fluids on heat capacity

4.3 The effects of section ratio and filling ratio on thermal resistance: Figure 8 indicates the effect of section ratio and filling ratio on thermal resistance with different working fluids. The thermal resistance increased with decreased evaporator length and the 40% and 80% acetone charged HPHXs shows the desired lower thermal resistance. The higher filling ratio results lower thermal resistances due to faster heat transfer rates. Nearly 63% reduction in thermal resistance pointed out with 80% acetone charged HPHXs then 40% DI charged HPHXs for SR_1.

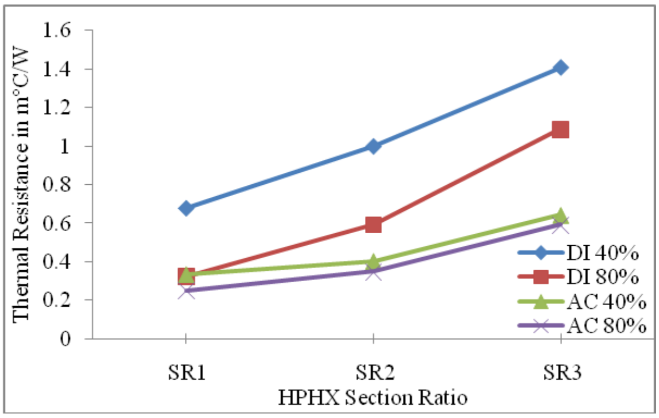

Figure 8: Effect of section ratio and filling ratio of different working fluids on thermal resistance

4.4 The effects of section ratio and filling ratio on temperature difference (ΔT): Figure 9 shows the variation of temperature difference due to section ratio and filling ratio. The temperature difference ranges between 43 °C and 95.9 °C in the experiments with HPHXs charged with acetone and distilled water at 40% and 80% of the evaporator. Due to the high heat transfer ability, the acetone charged HPHX results the lower range of 43 to 77.6°C temperature difference between the evaporator and the condenser sections. Meanwhile the 40% distilled charged HPHX shows the higher ΔT range of 63.7°C to 95.7°C.

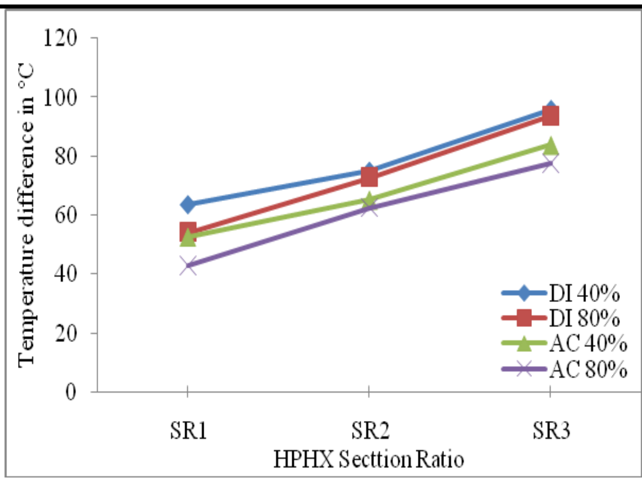

Figure 9: Effect of section ratio and filling ratio of different working fluids on temperature difference

4.5 The effects of section ratio and filling ratio on evaporator heat transfer coefficient (H_e): Figure 10 shows the convective heat transfer coefficient at evaporator sections at varied section ratio and the filling ratio of working fluid (acetone and distilled water). Among the two working fluid and two filling ratios the acetone charged HPHX with larger fill ratio (80%) shows the higher heat transfer coefficient for all the three section ratios SR_1, SR_2 and SR_3. Further, the SR_3 shows marginally higher values of evaporator heat transfer coefficient than SR_1 and SR_2. The 80% acetone charged HPHX shows the 'H_e' of 225.35, 242.69 and 286.82 W/m²°C for SR_1, SR_2 and SR_3 respectively.

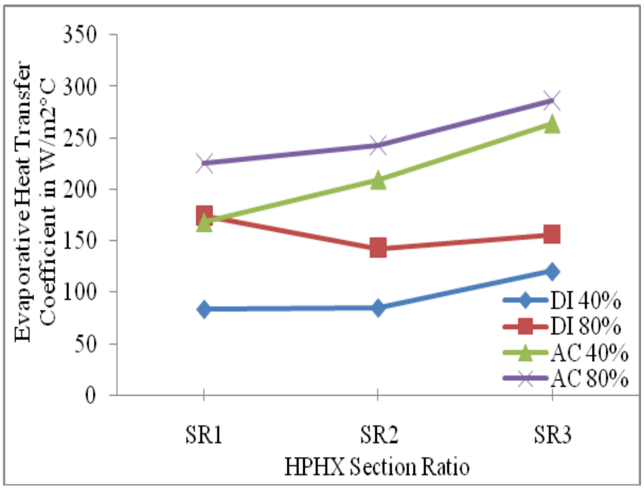

Figure 10: Effect of section ratio and filling ratio of different working fluids on evaporative heat transfer coefficient

4.6 The effects of section ratio and filling ratio on condenser heat transfer coefficient (H_c): The condenser heat transfer coefficient at the condenser section decreased with increased section ratio and larger condenser sections shows lower heat transfer coefficient due to the larger volume of condenser fluid , which takes more time to gets heated (Figure

11). Both the working fluid at different filling ratio shows the lower heat transfer coefficient for SR_3. The maximum heat transfer coefficient of 151.7 W/m²°C observed with 80% acetone charged HPHX for SR_1.

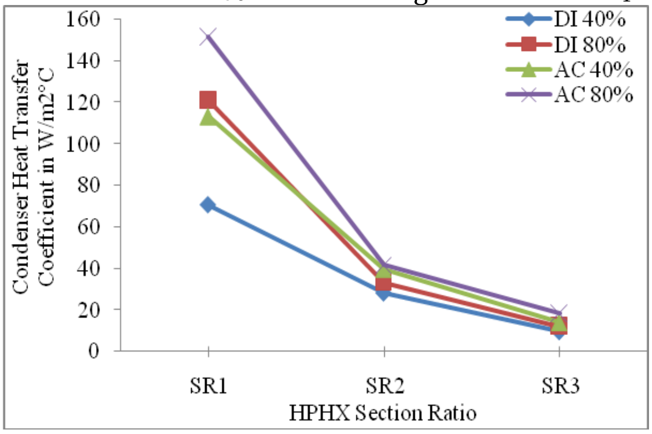

Figure 11: Effect of section ratio and filling ratio of different working fluids on condenser heat transfer coefficient

4.7 The effects of section ratio and filling ratio on biodiesel viscosity: Figure 12 shows the effect of section ratio and filling ratio of different working fluids on kinematic viscosity of biodiesel. The lower desirable viscosity is observed with HPHXs designed with SR_1 for both working fluids and filling ratios. The biodiesel viscosity increased with increased section ratio for both filling ratio and working fluids. Further the higher filling ratio and the acetone shows the lower viscosity values with the entire section ratio. The 80% acetone charged HPHX with SR_1 reduce the viscosity of biodiesel from 6.5 cSt to 2.3 cSt, which is closure to the viscosity of diesel fuel.

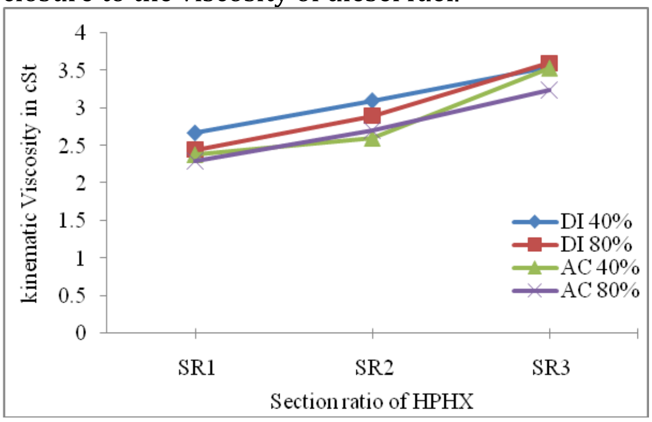

Figure 12: Effect of section ratio and filling ratio of different working fluids on kinematic viscosity of biodiesel

Conclusions

The unique HPHXs developed with three different section ratios and filled with acetone and distilled water as working fluid at 40% and 80% of evaporator volume. The designed and fabricated HPHX embedded to the engine at its exhaust side for the recovery of exhausted waste heat. The recovered waste heat is utilized for the preheat pongamia biodiesel to reduce its viscosity.

The following conclusions were drawn from the experimental results:

- There is remarkable decrease in viscosity of pongamia biodiesel. The 80% acetone charged HPHX with SR1 reduce the viscosity of biodiesel from 6.5 cSt to 2.3 cSt, which is closure to the viscosity of diesel fuel.
- The increased section ratio and decreased aspect ratio shows decreased effectiveness, heat capacity, temperature difference irrespective of working fluid and its filling ratio.
- The higher filling ratio results lower thermal resistances due to faster heat transfer rates.
- The 80% acetone charged HPHX shows the higher evaporator and condenser heat transfer coefficient of 286.82 W/m2° C and 151.7 W/m2° C for SR_3 and SR1 respectively.
- The acetone charged HPHX results the lower range of 43 to 77.6 °C temperature difference between the evaporator and the condenser sections. Meanwhile the 40% distilled charged HPHX shows the higher ΔT range of 63.7 °C to 95.7 °C.
- The effectiveness varies from 0.272 to 0.717 in the experiments. Further, the acetone charged HPHX with 80 % filling ratio presents the higher effectiveness of 0.717 irrespective of section ratio and aspect ratio.

It can be concluded that the effectiveness, thermal resistance and the heat capacity are the function of the temperature difference between evaporator and condenser, which in turn depends on the evaporator volume and the physical properties of working fluids. It can be confirmed that the effectiveness of heat pipe can be improved by modification of the section ratio and filling ratios.

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References

[1] P K Nag, "*A Text book on Heat and mass transfer*", second edition, Tata Mc Grawhill publishing company limited, 2008.

[2] Arora, S. C. and S. Domkundwar, "*A Course in Heat and Mass Transfer*", J. C. Kapoor, New Delhi, 1987.

[3] Luis Santiago, Andrés Felipe 'Model Design, Construction and Test of a Prototype of Heat Exchanger using Two-Phase Thermosyphons ", *Third LACCEI International Latin American and*

Caribbean Conference for Engineering and Technology (LACCET'2005), "Advances in Engineering and Technology: A Global Perspective", 8-10 June 2005, Cartagena de Indias, COLOMBIA

[4] S. H. Noie, M. Lotfi, Saghatoleslami "Energy conservation by waste heat recovery in industry using thermosyphon heat exchangers", *Iranian Journal of Science & Technology*, Transaction B, Vol. 28, No. B6 Pp 707-712.

[5] Srimuang W, Rittidech S, Bupchot B. "Heat transfer characteristics of a vertical flat thermosyphon (VFT)", *International journal of Mechanical Science and Technology*. 2009; 20: 781-90.

[6] Amatachaya P, Srimuang W. "Comparative heat transfer characteristics of a flat two-phase closed thermosyphon (FTPCT) and a conventional twophase closed thermosyphon (CTPCT)", *International Communications in Heat and Mass Transfer*. 2010; 37: 293-98.

[7] Noie SH, Majidian GR. "Waste heat recovery using heat pipe heat exchanger for surgery room in hospitals", *Applied Thermal Engineering*. 2000; 20(14): 1271-82.

[8] Lukitobudi AR, Akbarzadeh A, Johnson AW, Hendy P. "Design, construction and testing of a thermosyphon heat exchanger for medium temperature heat recovery in bakeries", *Heat Recovery Systems*. 1995; 15(5): 481-91.

[9] Habeebullah M H, Akyurt M, Najjar YSH, El-Kalay AK. "Experimental performance of a waste heat recovery and utilization system with a looped water in steel heat pipe", *Applied Thermal Engineering*. 1998; 18: 595-607.

[10] Riffat S B, Gan G. "Determination of effectiveness of heat-pipe heat recovery for naturally-ventilated buildings", *Applied Thermal Engineering*. 1998; 18: 121-30.

[11] Yang F, Yuan X, Lin G. "Waste heat recovery using heat pipe heat exchanger for heating automobile using exhaust gas", *Applied Thermal Engineering*. 2003; 23: 367-72.

[12] Noie SH. "Investigated the thermal performance of an air to air thermosyphon heat exchanger", *Applied Thermal Engineering*. 2006; 26: 559-67.

[13] Zuo, Z. J., and Gunnerson, F. S., 1995, "Heat Transfer Analysis of a Inclined Two Phase Closed Thermosyphon", *Journal of Heat Transfer*, Vol. 117,pp. 1073-1075

[14] El-Genk, M. S., Saber, H. H., "Determination of operation envelopes for closed two-phase thermosyphons", *International Journal of Heat and Mass Transfer,*42(5), 1999, 889-903

[15] Rodbumrung, S. Rittidech and B. Bubphachot, "Influence of working fluids, working temperature and evaporator length on internal pressure and damage behavior of the close loop oscillating heat pipe with check valves (CLOHP/CV)", *Australian Journal of Basic and Applied Sciences*, 5(12): 1411-1417, 2011.

[16] Hudakorn, P. Terdtoon and P. Sakulchangsatjatai, "Effect of inclination angle on performance limit of a closed-end oscillating heat pipe", *American J. of Engineering and Applied Sciences* 1 (3): 174-180, 2008.

[17] Noie,S.H.,"Heat transfer characteristics of a two-phase closed thermosyphon". *Applied Thermal Engineering*, 2005. 25(4): p. 495-506.

[18] M. H. M. Grooten.; and C. W. M. van der Geld. Predicting Heat Transfer In Long, R-134a Filled Thermosyphons, *Technische Universiteit Eindhoven*, Postbus 513, Eindhoven,Netherlands..

[19] Donald T.W, Hwang K.S and R. Diciccio. 1977."Thermosiphon loop performancecharacteristics": Part 1. Experimental study.Trans. ASHRAE, 83:250–259.

[20] Chen, M. M., Faghri, A., and Morgan, M. (1989), "Heat Transfer Characteristics in Two Phase Closed Conventional and Concentric Annular Thermosyphons", ASME Trans. J. of heat Transfer, Vol. 111, No. 3, pp. 611-618.

[21] Tun-Ping Tenga, How-GaoHsua, Huai-En Mob,Chien-ChihChenc "Thermal efficiency of heat pipe with alumina nanofluid", *Journal of Alloys and Compounds*,504S, S380–S384, 2010.

[22] M. Kannan, R. Senthil, R. Baskaran and B. Deepanraj "An experimental study on heat transport capability of a two phase thermosyphon charged with different working fluids" *American Journal of Applied Sciences* 11 (4): 584-591, 2014.

[23] I Khazaee, R. Hosseini, S.H. Noie, "Experimental investigations of effective parameters and correlation of geyser boiling in a two phase closed thermosyphon", *Applied Thermal Engineering*, Vol.30, 2010, pp.406-412.

[24] Amir Faghri (1995). "Heat pipe Science and Technology". United States of America. Taylor and Francis, 1995. ISBN: 1560323833.