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RESEARCH ARTICLE

EXPERIMENTAL INVESTIGATIONS ON GRAVITY ASSISTED HEAT PIPE HEAT EXCHANGER FOR ENGINE EXHAUSTED HEAT UTILIZATION

*[1]Nadaf, S. L. and [2]Gangavati, P.B.

[1]Mechanical Engineering Department, Government Engineering College, Haveri-581110, India
[2]Mechanical Engineering Department, Basaveswar Engineering College, Bagalkot-587102, India

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ABSTRACT

The paper presents experimental investigations carried out on a stationary diesel engine at a constant speed and full load with preheated pongamia biodiesel. The preheating of pongamia biodiesel attempted with the help of gravity assisted heat pipe (Thermosyphon) heat exchanger. The heat exchanger designed to utilize the engine exhausted waste heat to preheat the biodiesel. The experiments were conducted to investigate the influence of different geometric and physical parameters of heat pipe heat exchangers (HPHX) on heat transfer characteristics. The effect of preheating on engine performance and emissions were also studied and compared with diesel. The 80% acetone charged HPHXs exhibit better results in respect to the performance of HPHX and the engine. The maximum effectiveness of 0.757 achieved for 80% acetone HPHX with section ratio 1:3(SR1), Aspect ratio (AR) 10 and tube diameter D_3. The tubes with larger diameter and evaporator length show lower thermal resistance, higher BTE much near to diesel fuel. The preheating tends to reduce CO, HC and smoke emissions, while increasing emission of CO_2, NO_x and EGT leaving the engine.

INTRODUCTION

Nowadays, environment pollution and limitations in energy resources appeared as a serious global crisis. Hence, the energy conservation and energy efficiency are necessary in all energy devices including the internal combustion engines(IC). The waste heat recovery techniques with features of being energy-saving and environment-friendly, have received significant attention (Khan *et al*., 2002). The present energy scenario has stimulated active research interest in renewable and non-polluting fuels. Increased dependence on imported fuel and regulations on the exhaust emissions of vehicles established by the Environmental Protection Agency (EPA) has increased the need for alternative fuels. But some of the alternative fuel does not have good properties, the properties related to fluidity and their viscosity. A majority of energy is dissipated as heat in the exhaust and coolant from engines. It is evident from the researches that engines emitted app. 30-40% of heat generated to the environment through the exhaust gases which is in the range of 250º C to 450º C (approx.) this high temperature might be used in an efficient way. If the waste heat were put to appropriate use, there would be great energy or fuel savings. Rather than directly improving the efficiency of the engines, the efforts are being made to improve the efficiency of the engine indirectly by using a waste heat recovery system (Orr *et al.,* 2015).

Corresponding author: Nadaf, S. L.
Mechanical Engineering Department, Government Engineering College, Haveri-581110, India.

The attempt can make to ascribe the waste heat energy available, which makes research into the recovery of waste energy and subsequent utilization for fuel improvement i.e. reduce the viscosity of biodiesel. To recover heat energy from exhaust gas some type of device is required, which can efficiently transfers the heat from exhaust gases to the fuel. Among the various waste heat recovery (WHR) and utilization systems, the heat pipe heat exchangers are one of the attractive devices used in waste heat recovery. This research paper focused on the influence of geometrical and physical parameters of HPHX on its performance and the effect of preheating biodiesel on engine performance and emissions. The diesel engine exhaust heat utilization to reduce viscosity of biodiesel has the potential to reduce the consumption of fossil fuels and reduce the release of greenhouse gases. A critical component in this research, and in any waste heat recovery system, is the heat exchanger that extracts the heat from the exhaust.

The Heat Recovery from IC Engines

There are many heat recovery methods available for capturing engine waste heat, including thermal electric conversion; heat-to-power conversion, direct heat application, heat for refrigeration and air conditioning. Kruiswyk (2008) detailed the components, technologies, and methods to recover energy from exhaust of IC engines and utilize to improve engine efficiency by 10%. Rathavi (2012) recovered large part of waste heat by vaporizing the fuel through a small heat exchanger and reduced the boiling point of fossil fuels by 50%. Also they attained significant reduction of engine fuel consumption and hazardous emissions. Jiricek (2007) designed a steam sterilization system to provide proper sterilization and cleaning of medical equipment decreasing the dependency on electricity, this system uses waste engine heat from exhaust system of a diesel generator set. Desai and Bannur (2001) designed and fabricated a shell and tube heat exchanger to extract waste heat from the exhaust gas of an IC engine. Nisar and Bari (2010) conducted experiments on shell and tube heat exchanger using water as the working fluid to measure the exhaust waste heat available from a 60 kW automobile engine. Acharya *et al.* (2011) designed shell and tube heat exchanger to reduce viscosity of kusum and karanja oil's. The engines exhaust gas used as source for preheating. Navindgi *et al.* in 2012 (Neem, Mahua,Linseed and Castor oil) ; Agarwal *et al.* in 2009 (Karanja oil); Khatri *et al.* in 2010 (Karanja); Chauhan *et al*. in 2010 (Jatropha); preheated the different vegetable oil using the waste heat recovered by heat exchangers from engine exhaust. Raghu *et al.* (Rice bran oil) preheated the different biodiesels using the waste heat recovered by heat exchangers from engine exhaust. Vijittra *et al*.(Jatropha oil); Ingle *et al*.(cottonseed methyl ester); Kadu *et al.(*Karanja oil) ; Suresh *et al.(*coconut oil); Mitra *et al.*(karanja oil); Rao (Karanja methyl ester) preheated the different vegetable oil and their derivatives using the electric heaters.

Preheated Karanja Oil and Their Derivatives

The fuel preheating techniques offer superior characteristics for heavy fuels to work on diesel engines (Nwafor, 2003). Sonune *et al*. (2012) reported that the preheated vegetable oil, a good alternative fuel for diesel engines. Preheating by exhaust gases could be one feasible solution to overcome the problem of high viscosity which is being the major cause of many problems. Mitra and Basu (2011) studied the performance of diesel generator using pongamia oil preheated at 50-200°C. The significance improvements in pollution of exhaust had been observed. The best performance found at oil inlet temperature of 122 °C. Agarwal and Rajamanoharan (2008) reduced viscosity of Karanja oil and its blends by a specially designed heat exchanger utilizing waste heat from exhaust gases. The Significant improvements have been observed in the performance parameters of the engine as well as exhaust emissions. Hossain (2012) preheated jatropha and karanj oils using cooling water circuit prior to injection. Panigrahi et al. (2014) reduced the viscosity of straight karanja oil by preheating up to 160º C under different load condition. The preheating was done with the help of a shell and tube heat exchanger and the heating source was waste exhaust gas from engine. Kadu et al. (2010) directed their efforts towards improving the performance of C.I engines by preheated neat Karanja oil at 30 °C to 100 °C. Patil et al. (2012) investigated the diesel engine fuelled with Karanja oil and its blends with and without preheating using exhaust gas heat exchanger. Rao (2011) conducted engine tests using karanja methyl ester (with and without preheat) and compared with baseline diesel. A significant reduction in oxides of nitrogen emission is observed with preheated methyl ester.

Factors influence performance of heat pipe heat exchanger

Heat pipes are known for being part of the most efficient heat transfer devices today. The first working heat pipe was developed by Jacob Perkins in 1836 and was called as Perkins Tube (Perkins 1836). Zuo and Gunnerson (1994) studied the steady state performance of the gravity-assisted two-phase closed thermosyphon by varying different parameters like operating temperatures, geometry, working fluid inventory and condenser thermal capacity. The geometric parameters include aspect ratio (AR), section ratio (SR), length of various sections of the heat pipe, diameter of heat pipe and the thickness of container material etc. The rate of at which the working fluid returns from the condenser to the evaporator is governed by capillary limit and is the reciprocal function of the heat pipe's length. El-Genk and Saber (1999) developed a heat pipe with specified working fluids, 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 heat pipe (thermosyphon)*. Yamamoto (2008), reported that the larger the pipe diameter, the greater the maximum heat transfer rate. Peterson (1994) stated the liquid transport length of the working fluid has a significant influence on the heat transport capability. The shorter the liquid transport length, the larger the heat transport capability. Hudakorn (2008) concluded that the critical heat flux increases with an increase in the inner diameter. Shivaraman *et al.* (2005) conducted experiments to present the effect of L/d_i ratio of the copper-water heat pipe. The collector with L/d_i ratio of 52.63 was found to be more efficient than the L/d_i ratio of 58.82 i.e. the decreased ratio leads to the increased heat transfer capacity.

Kannan *et al*. (2014) reported that the maximum heat transport capability of water is high compared to ethanol, methanol and acetone at all filling ratios and at all operating temperatures. Khazaee *et al.* (2010) investigated the effect of filling ratio, aspect ratio, heat input and mass flow rate on the heat transfer characteristics with methanol as a working fluid. Jouhara and Robinson (2011) investigated a small diameter and compact thermosyphon with four different working fluids: water, Fluro Carbon(FC)-84, FC-77 and FC-3283 and reported that thermal performance of the water charged thermosyphon outperformed the other three working fluids in both the effective thermal resistance as well as maximum heat transport capabilities. Rodbumrung *et al*. (2011) conducted experiments with Water, ethanol and R123 as working fluids with the filling ratio of 50%. The test in vertical orientation carried with working temperature increased from 200 °C to 400 °C. It was found that, ethanol as good working fluid.

MATERIALS AND METHODS

The commercially available pongamia biodiesel which conforms to the standards specified in ASTM-D-6751 is used in the present study. The biodiesel is derivative of vegetable oil and made through a chemical process named transesterification. The methyl ester (biodiesel) produced from pongamia oil is known as pongamia oil methyl ester (POME) or Pongamia biodiesel. The various instrument used for the determination of biodiesel properties in the testing laboratory and the corresponding ASTM methods are tabulated in the Table I. The thermosyphon is also known as gravity-assisted heat pipe or wick-less heat pipe. The operating principle is almost identical. Instead of a wick structure the working fluid is returned to the evaporator using gravity forces. Therefore, the only restriction compared to a heat pipe is that the thermosyphon must be oriented (reasonably) vertically with the heated area on the bottom side as shown in Fig. 1.

Table 1. The Instruments & ASTM Methods Used To Measure Fuels Properties

Properties	*Unit*	*Instrument used*	*ASTM methods*
Kinematic viscosity	Cst	Red wood Viscometer	D445
Density	gm/m3	Hydrometer	D1298
Flash point and fire point temperature	ºC	Pensky Martens apparatus	D93
Calorific value	KJ/Kg K	Bomb calorimeter	D240
Copper strip corrosion		copper strip corrosion test bomb	D130

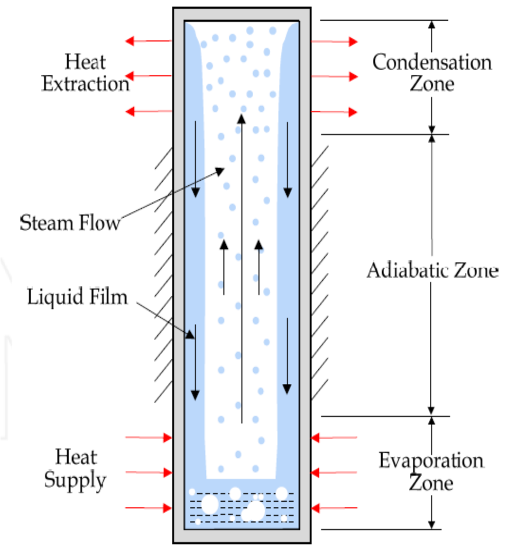

Fig. 1. Schematic of two phase closed thermosyphon (Noie & Lotfi, 2001)

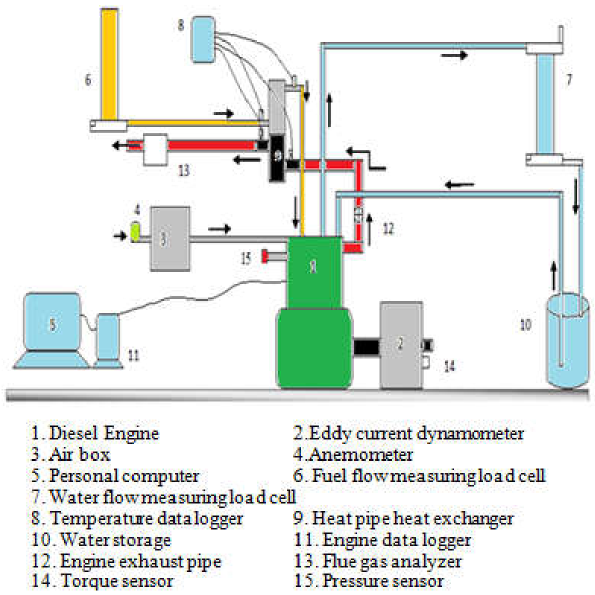

Fig. 2. The experimental test rig

Fig. 2 shows the schematic diagram of experimental test set up with heat pipe heat exchanger and all the necessary instrumentation for online data access and measurement. It consists of a single cylinder, 4 stroke diesel engine, an eddy current dynamometer, duel fuel tank, speed & torque sensors, data acquisition system, computer, operation panel, exhaust emission analyzers, and the temperature data logger. *For preheating POME*; heating devices, the heat pipe heat exchanger placed along the fuel discharge line as shown in Fig. 2.

The fuel injection was performed at a static injection timing of 23° BTDC set for diesel fuel. The engine is allowed to warm up at constant speed, until the temperatures reaches a steady state. Eddy current dynamometer is used to measure the torque. A computer interfaced piezoelectric sensor of range 0 to 145 bar was used to record the in-cylinder pressure. Pressure signals were obtained using data acquisition system. The preheated biodiesel is directed to the engine injector through an insulted steel wired pipe to avoid the cooling of biodiesel. The exhaust gas passed through the evaporator portion of heat exchanger and finally expelled to the atmosphere after flue gas analyzer and smoke meter.

Engine

In India, almost all irrigation pump sets, tractors, mechanized farm machinery and heavy transportation vehicle are powered by direct injection diesel engine. A typical engine system detailed in Table 2, which is widely used in the Indian agricultural sector, has been selected for the present experimental investigations. The Fig. 3(a-e) shows the different sensors used for the measurements of most important parameters.

Fig. 3. The different sensors used for the measurements a) Piezoelectric pressure sensor b) RTD Temperature sensor c) Proximity speed sensor d) Strain gauge load cell based torque sensor and e) Velocity sensor.

Exhaust Flue Gas Analyzer

The engine emissions were measured with the exhaust gas analyzer (make: MRU, Germany and model: Delta 1600 L) shown in Fig. 4 and the Table 3 shows the technical specifications of the exhaust gas analyzer used. The exhaust gas is made to pass through the flue gas analyzer probe and is later passed through the probe of smoke meter for the measurement of smoke opacity. The emissions like HC, CO, NO_x, CO_2 and O_2 and the smoke opacity recorded online.

Table 2. Technical Specification of the Engine

Detail	*Specification*
Engine type	AV1 5HP Vertical, single cylinder, water-cooled, 4-stroke cycle, C I diesel engine.
Make	Kirloskar
No. of Cylinders	1
Bore x Stroke (mm)	80 X 110
Compression Ratio	16.5 : 1
Rated Output as per IS: 11170 kW(hp)	3.7(5)
Rated Speed rpm	1500
Dynamometer and Torque Measurement	Air cooled Eddy Current Dynamometer , Load cell 0-40kg with digital indicator
Air flow Measurement	Differential pressure transducer with digital indicator
Fuel, Water flow measurement	Load cell based, loss in weight type with digital indicator
Temperature Measurement	PT 100 sensors for low temperature measurement and K type thermocouple for high temperature with indicator.
Speed Measurement	Digital speed indicator with proximity sensor
Communication	All the indicators communicated with RS-485 output and an RS converter is provided with 2 meter communication cable.
Software	Lab View based Software suitable for performance Analysis(Software “IEAS”)
Crank Angle Measurement	TDC encoder is provided to measure crank angle having 1dg resolution.
Starting	Hand Start
Type of fuel injection	Direct Injection

Smoke Opacity Meter

The Smoke opacity meter of MRU make Germany and Optrans 1600 Model; is used in the present work for the online smoke measurement of stationary engine exhaust. It’s provided with the digital display as shown in Fig. 5.

Fig. 4. Flue gas analyzer

Table 3. Make, model of flue gas analyzer

Make	MRU, DELTA 1600 S, Germany	Resolution
O_2	Electrochemical	0.01%
NO_x	Electrochemical	1 ppm
CO	NDIR - Resolution	0.01%
CO_2	NDIR - Resolution	0.1%
HC	NDIR- Resolution	1 ppm

Fig. 5: The smoke opacity meter and the digital display

Installation and Instrumentation of HPHX Assembly

The assembled heat pipe heat exchanger shown in the Fig. 6 is a bundle of heat pipes integrated to engine at its exhaust side.

Fig. 6. The Heat pipe heat exchanger assembly

The RTD thermocouples are connected at the inlet and exit of HPHX for hot (Engine exhaust) and cold fluid (Biodiesel) as in the Fig. 6. The thermocouples in turn connected to the temperature data logger and communicated to the computer for online data access and storage. The data logger is microprocessor based, 12 channel with 3.5” color display, MS powder coated cabinet with output communication to the PC software by RS 232 data cable.

Section Ratio and Heat Pipe Pattern in Heat Exchanger

Fig. 7 shows the section ratio of heat pipe heat exchangers for the optimization of heat exchanger: SR_1, SR2 and SR_3 (1:3, 1:1 and 3:1 respectively). The heat pipes of three different diameters D_1, D_2 and D_3 (12.7mm, 19.05mm and 25.04mm respectively) were used for each section ratios. The Figure also shows triangular (rotated square) patterns of tube in the heat exchanger shell. The triangular arrangement allows more tubes in a given space.

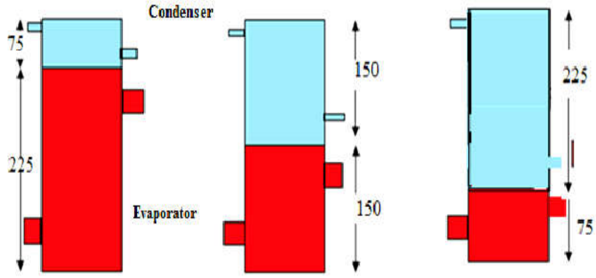

Fig. 7. Tube layout and section ratio of HPHXs

The Table 4 enlists the experimental matrix of HPHX with variable geometric and physical parameters:

Table 4. The matrix of hphx with variable parameters

Type	Copper,Vertical bundle, wickless and gravity assisted, without adiabatic section								
Geometric Properties									
L_{co} (mm)	75			150			225		
L_{ev} (mm)	225			150			75		
SR:Lc/Le	SR_1 1:3			SR_2 1:1			SR_3 3:1		
Diameter	D_1	D_2	D_3	D_1	D_2	D_3	D_1	D_2	D_3
(mm)	12.7	19	25	12.7	19	25	12.7	19	25
AR, Le/di	22	14	10	15	9	6.6	7.4	4.5	3.3
Physical Properties									
Working fluid	Distilled Water(DI) and Acetone(AC)								
Filling Ratio	40 % & 80% of evaporator volume								

RESULTS AND DISCUSSION

The stationary engine is tested with preheated pure pongamia methyl ester (POME) and compared with baseline diesel. The engine tests were focused on the heat exchange features of HPHXs and the exhausted waste heat utilization in reducing pongamia biodiesel viscosity. The effect of biodiesel preheating on engine performance and emissions were also analyzed.

Heat Exchange Features of HPHXs

The influences of different geometrical and physical parameters on thermal performance of HPHX were studied at full engine load supplied with pure biodiesel.

Effect on Waste Heat Recovered (Heat Capacity)

The "Heat capacity" represents the total heat transfer rate in account of boiling and condensation heat transfer through HPHXs. The Fig.8 shows the variation of heat capacity of 40% and 80% distilled water (DI) and acetone (AC) charged HPHXs at different section ratio and aspect ratio. The heat recovered increased with decreased AR and increased tube diameter from D_1 to D_3 irrespective of section ratio. It's also observed that the SR_1 shows maximum heat capacity for both the working fluids at different fill ratio. The maximum heat recovery of 40.78844 W is observed for 80% AC charged HPHXs with D_3 and SR_1. The HPHXs with lowest aspect ratio for each section ratio shows the highest heat recovery irrespective of working fluid and its fill ratio. The HPHX with SR_1 & D_3 shows 20.04% and 20.33 % higher heat recovery than SR_2 and SR_3 respectively.

This is due to the fact that the increased tube diameter and evaporator volume offer more surface area for exhaust heat leads for increased heat transfer.

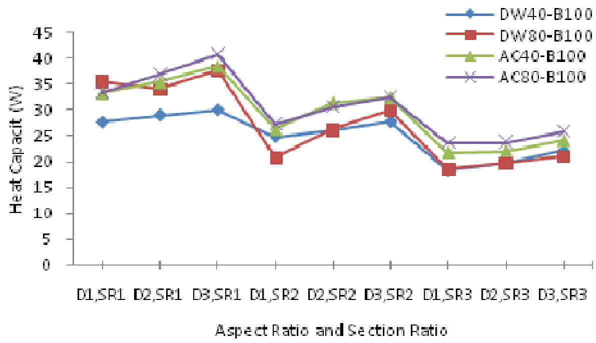

Fig. 8. Effect of section ratio and aspect ratio on heat capacity

Effect on Thermal Resistance

The thermal resistance is function of thermal gradient and heat input. For better heat transfer the thermal resistance has to be on a lower side. Fig. 9 represents a direct comparison for thermal resistance for different aspect ratio and section ratio. The increased heat flux decreases the inner thermal resistance for the pipes as a result of the increased tube diameter and large evaporator length. An observation can be drawn that the 80% AC charged HPHX with SR_1 shows minimum thermal resistance for all section ratio and aspect ratios. The DI 40% HPHX shows higher resistance for all section ratio and aspect ratios. For maximum tube diameter (lower AR) for all section ratios, the thermal resistance is found to be decreased irrespective of working fluid and its fill ratio.

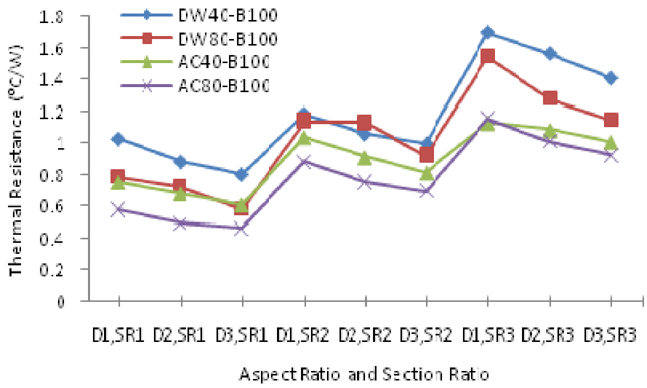

Fig. 9. The effect of section ratio and aspect ratio on Thermal resistance

Effect on Effectiveness

Fig. 10 illustrates the variation of effectiveness with Aspect ratio (tube diameter) and section ratio (evaporator length). The increased diameter of heat pipe results in an increase in the temperature change & the increase in the effectiveness of the exchanger. From the Figure 10, the maximum effectiveness of 0.757 observed for 80% acetone charged HPHXs with $SR_1$and D_3. The effectiveness of 80% acetone charged HPHXs are nearly 30% higher than DI for all section ratio and aspect ratios. The higher effectiveness is due to the higher heat input at HPHXs inlet and the reduced ignition delay due to preheat. The maximum effectiveness of 0.757, 0.633 and 0.4958 observed for HPHXs with SR_1, SR_2 and SR_3 respectively for D_3. This indicated that the acetone charged HPHXs works better than water charged HPHXs due to higher heat capacity of acetone. The average effectiveness of HPHXs with SR_1 is 16.14% and 36.70% higher than SR_2 and SR_3 respectively. The decreased aspect ratio shows 12.02%, 13.15% and 16.91% increased effectiveness for SR_1, SR_2 and SR_3 respectively for 80% acetone charged HPHXs.

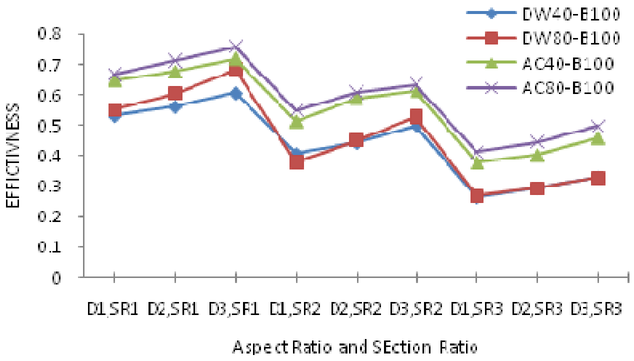

Fig. 10. Variation of effectiveness with different aspect ratio and section ratio

Effect on Efficiency

From the Fig.11 it's seen that the SR_1 shows the higher efficiency of heat conversion than the SR_2 and SR_3 which is due to the larger evaporator volume.

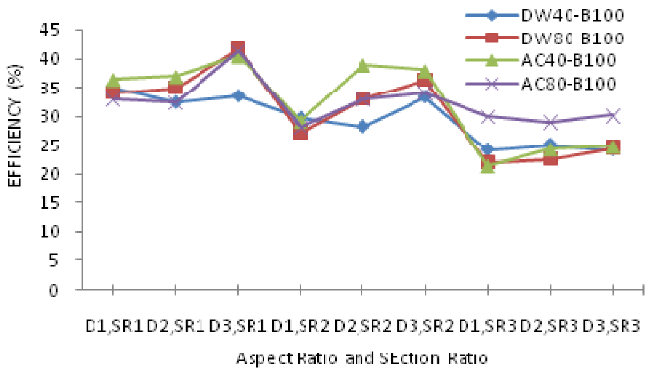

Fig. 11. Effect of section ratio and aspect ratio on thermal gradient

The efficiency increases with increased tube diameter (Reduced Aspect Ratio). Also the HPHXs with larger diameter (D_3) show the maximum efficiency of 41.245%, 34.1% and 29.99% for SR_1, SR_2 and SR_3 respectively. It's also seen that the HPHXs charged with acetone shows the better efficiency in comparison with distilled water irrespective of fill ratio. The acetone charged HPHXs shows the maximum efficiency irrespective of aspect and section ratio. Meanwhile the DI charged HPHXs shows the lower efficiency.

Effect on Heat Transfer Coefficient

Fig.12 shows heat transfer coefficient (H_e) plotted v/s HPHX of different section ratio and aspect ratio charged with distilled water and acetone at 40% and 80% of evaporator volume. The acetone charged HPHXs shows the higher heat transfer coefficient than distilled water.

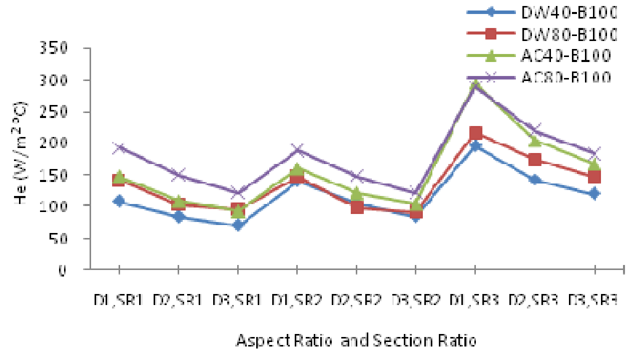

Fig.ure 12. Effect of section ratio and aspect ratio on heat transfer coefficient

The highest heat transfers coefficient is observed for 80% Acetone charged HPHXs at lowest AR at all section ratios. Also the larger fill ratio of acetone and distilled water exhibit larger heat transfer coefficient. The value of heat transfer coefficient decreases with the decrease in AR and increased tube diameter. It is also observed that the larger evaporator (SR_1) volume shows lower heat transfer coefficient. The heat transfer coefficient of 80% Acetone HPHXs is nearly 71% higher than that of 40% DI HPHXs for all Aspect ratio and section ratio.

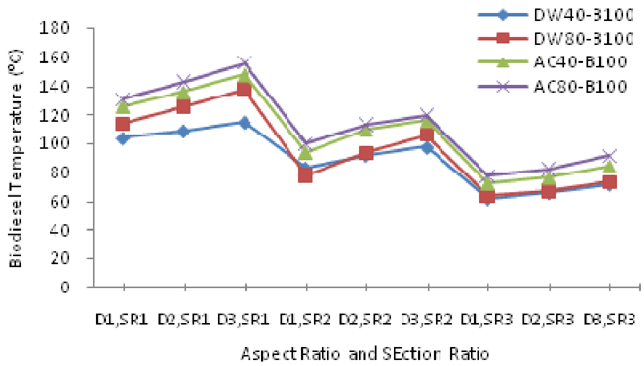

Fig. 13. Effect of section ratio and aspect ratio on biodiesel temperature

Heat Exchange Utilization

The effect of preheating on the biodiesel temperature and the corresponding biodiesel viscosity entering the engine cylinder are monitored, recorded and are as shown in Fig. 13 and Fig. 14.

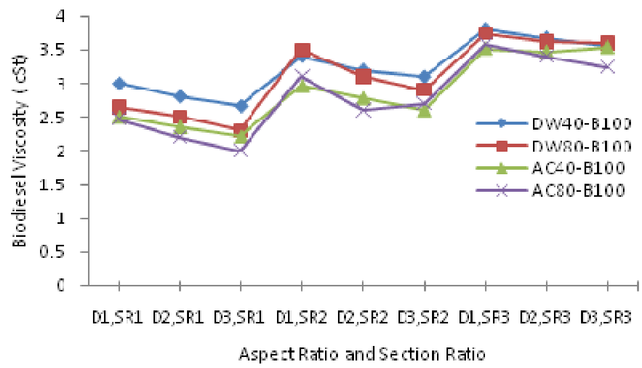

Fig. 14. Effect of section ratio and aspect ratio on biodiesel viscosity

The viscosity reduced with increased heat pipe tube diameter from 12.7 mm to 25mm in each section ratio. It is observed from Fig. 14 that the HPHXs with D_3 show lowest viscosity of 2.6 cSt almost equal to diesel. This is attributed to the higher temperature of biodiesel leaving the condenser due to preheat with exhausted engine heat. The acetone charged HPHXs results higher biodiesel temperatures and hence the lower viscosities at all aspect and section ratio.

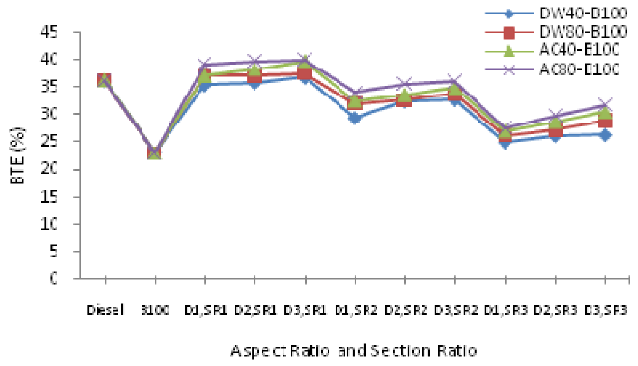

Fig. 14. Effect of section ratio and aspect ratio on biodiesel viscosity

Engine Behavior with Preheating

The effect reduced viscosity due to preheating using HPHX on engine performance and emissions were studied. The results obtained under full engine load conditions, are presented.

The Effect on Brake Thermal Efficiency (BTE)

Fig.15 shows the variation of BTE with section ratio and aspect ratio of HPHXs at different working fluid and filling

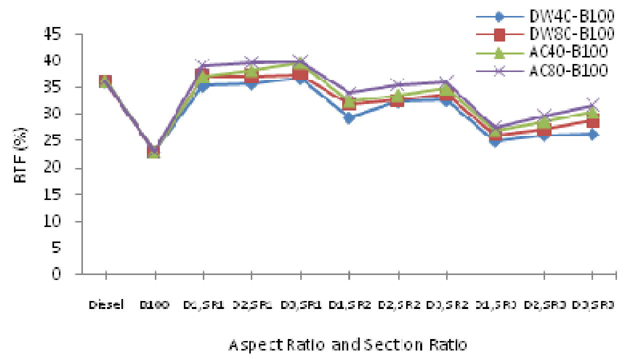

Fig. 15. Effect of section ratio and aspect ratio on BTE

It's seen that the 80% acetone charged HPHXs shows the maximum BTE higher than diesel irrespective of aspect ratio and section ratio. It's also observed that the SR_1 shows the highest BTE in comparison to SR_2 and SR_3. The HPHXs with D_3 shows 42.65%, 36.39% and 27.59% increase in BTE for SR_1, SR_2 and SR_3 respectively in comparison to unheated B100.

Effect on Brake Specific Fuel Consumption (BSFC)

The variation of BSFC with different working fluids and filling ratio using HPHXs of different aspect ratio (Le/Di) and section ratio is indicated in fig.16. The BSFC is slightly higher than diesel.

It's also observed that BSFC reaches its maximum value for biodiesel B100 due to lower calorific value. The HPHXs with SR_3 shows higher BSFC than SR_1 and SR_2 due to larger condenser volume and reduced heat transfer rates.

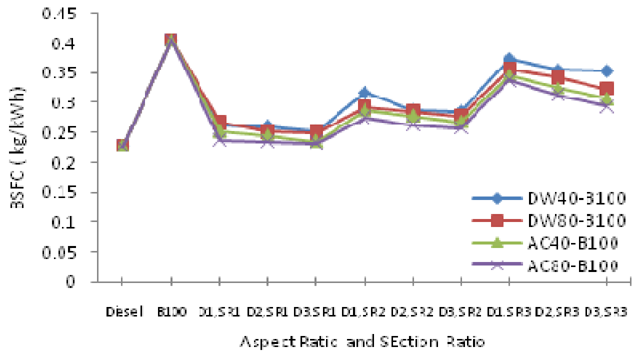

Fig. 16. Effect of section ratio and aspect ratio on BSFC

Effect on Oxygen Emission

The Fig. 17 presents the combined effect of geometrical and physical parameters of HPHXs on Oxygen emission keeping the operational parameters constant. It can be seen from the curves that there is no much significant variations but the oxygen emissions reduced significantly for preheated pure biodiesel in comparison to unheated biodiesel. The oxygen emission of preheated B100 is higher than the diesel fuel but is lower than unheated B100. The HPHXs with lowest AR (Higher diameter D_3) of SR_1, SR_2 and SR_3 shows 11.16%, 6.55% and 3.04% increase in oxygen emission for 80% acetone charged HPHXs supplied with B100 in comparison to diesel.

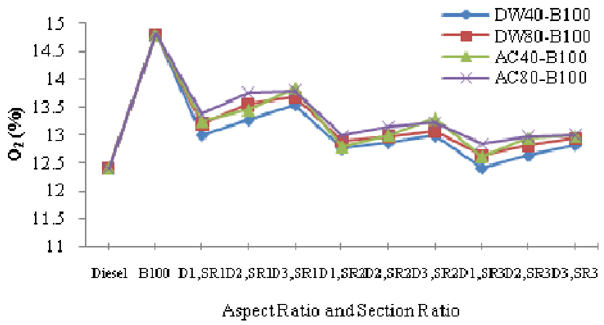

Figure 17. Effect of section ratio and aspect ratio on Oxygen emission

Effect on Carbon Dioxide Emission

Fig.18 shows the variation of carbon dioxide (CO_2) emission with three different aspect ratio (AR_1, AR_2 & AR_3) and three different section ratios (SR_1, SR_2 & SR_3) for HPHXs charged with acetone and distilled water at 40% and 80% fill volume. The CO_2 concentrations increase with decreasing aspect ratio (Increased tube diameter) for each section ratio. This is due to larger oxidation rate, which is caused by presence of extra oxygen in pure biodiesel. The CO_2 emissions of preheated B100 are higher than both the diesel and unheated fuels. It's also seen that the CO_2 increased with increased tube diameter for each section ratio. The maximum CO_2 observed are 8.9%, 8.6% and 8.5% for SR_1, SR_2 and SR_3 respectively. The average CO_2 emissions at the lowest aspect ratio (larger tube diameter) increased by 67.93%, 66.92% and 66.66% for SR_1,

SR_2 and SR_3 respectively. The increase tube diameter and larger evaporator lengths of HPHXs improves heat capacity and hence the reduced biodiesel viscosity and mixing process, leading to better combustion process. This leads to increasing CO_2 emissions. The 80 % acetone charged HPHXs shows the highest CO_2 emissions. This is attributed to higher fill ratio and higher specific heat of acetone to distilled water.

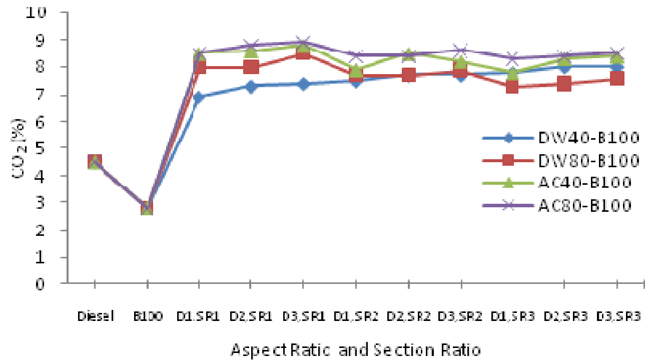

Fig. 18. Effect of section ratio and aspect ratio on carbon dioxide emission

Effect on Nitrogen Oxide Emission

Fig. 19 shows the variation of nitrogen oxides (NO_x) emission using WHR HPHXs with different geometrical and physical parameters. The NO_x emission increases with the increase in the tube diameter and decreased aspect ratio. The pure biodiesel shows slight higher NO_x emissions than diesel. But the preheated B100 using HPHXs charged with distilled water & Acetone at different filling ratio shows considerable increase in NO_x emissions. It's seen from the curves that the Acetone charged HPHXs show higher NO_x emissions than DI charged. The highest NO_x emissions of 850ppm observed for D_3 diameter HPHXs having section ratio SR_1 than SR_2 and SR_3. The increase in NO_x emissions with preheat is due to better combustion of biodiesel due to its high oxygen content, higher temperatures leading to improved fuel spray characteristics as a result of preheating.

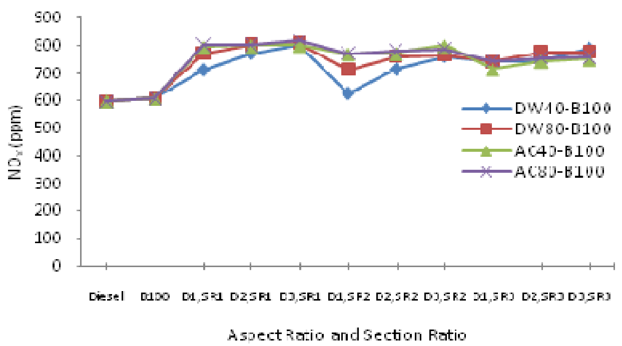

Fig. 19. Effect of section ratio and aspect ratio on nitrogen oxide emission

Effect on Carbon Monoxide Emission

Fig.20 depicts the variation in carbon monoxide (CO) emission as the geometrical and physical parameters of HPHXs varied. The CO emission predominantly influenced by the section ratio, aspect ratio, working fluid and its filling ratio. The CO emission with and without preheated B100 are lower than diesel fuel.

The CO emission reduced with increased tube diameter and the lowest values of CO emissions were noted for D_3 tube diameters and SR_1. It seems that the low viscosity of fuel due to the higher fuel preheat enhanced the fuel-air premixing and lower CO emissions. The acetone charged HPHXs shows the lowest CO emissions for all the AR and SR. When operated with B100 the HPHXs of D_3 diameter shows 58.33%, 50% and 33.33% reduction in CO emission for SR_1, SR_2 and SR_3 respectively. The significant improvement in CO emission was obtained after preheating for all HPHXs. The decreasing CO emission is more when preheating temperature is increased from D_1 to D_3 diameter. High oxygen content and reduced viscosity of biodiesel blends and due to preheating had good effect on complete combustion of fuel and reduced CO emission.

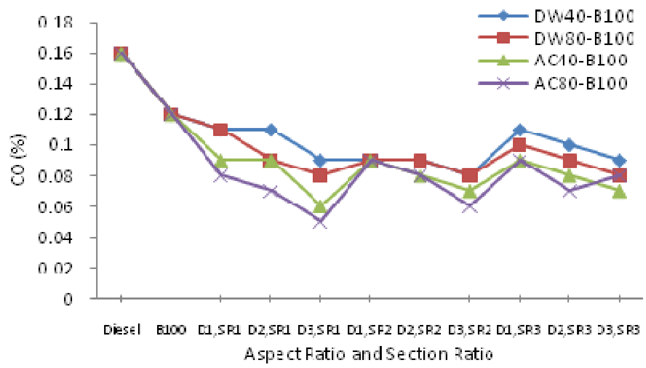

Fig. 20. Effect of section ratio and aspect ratio CO emission

Effect on Unburned Hydrocarbon (UBHC)Emission

The behavior of HC emissions influenced from aspect ratio and section ratio of HPHXs charged with different working fluid and their fill volume. This can be seen more conveniently from Fig. 21 under full load supplied with B100. The higher evaporator length and higher tube diameter results lower HC emission, which is indicated by SR_1 and D_3. The HC emissions for preheated B100 decreased with increased tube diameter. The 80% acetone charged HPHXs shows the lowest desirable HC emissions irrespective of aspect ratio and section ratio. This might due to the reduction in viscosity and subsequent improvement in spray, fuel-air mixing and combustion characteristics by preheating.

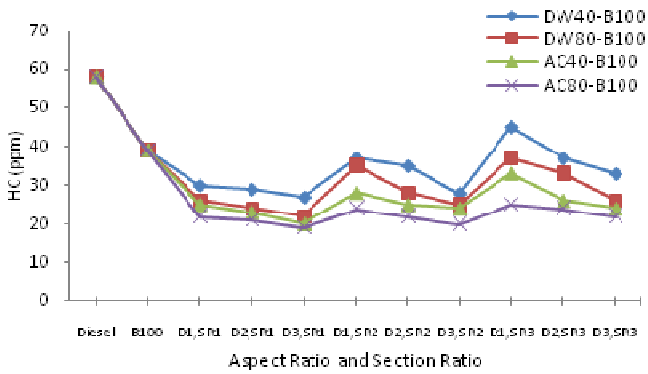

Fig. 21. Effect of section ratio and aspect ratio on hydrocarbons emission

Effect on Smoke Emission

Smoke is the visible product of diesel engine emission. From the plot, it is observed that smoke opacity of biodiesel is significantly lower than diesel.

At high temperatures biodiesel becomes less viscous & resulted in better atomization and vaporization and leads to complete combustion. This resulted in reduced smoke emissions. The variation of smoke is shown in Fig. 22. The biodiesel with and without preheat shows the lower smoke emissions than diesel duel at full engine load. This may be attributed to complete combustion because of oxygenated fuel. The complete combustion and fully utilized high oxygen content results lower smoke. It's also observed that the SR_1 shows lower smoke emissions than SR_2 and SR_3, but there is smaller variations seen by the varied working fluid and its fill volume. The acetone charge HPHXs shows better results than distilled water under all the section ratio and aspect ratio conditions. The 80% acetone charge HPHXs with D_3 diameter results in 52%, 40% and 36% reduction in smoke value for SR_1, SR_2 and SR_3 respectively when operated with B100.

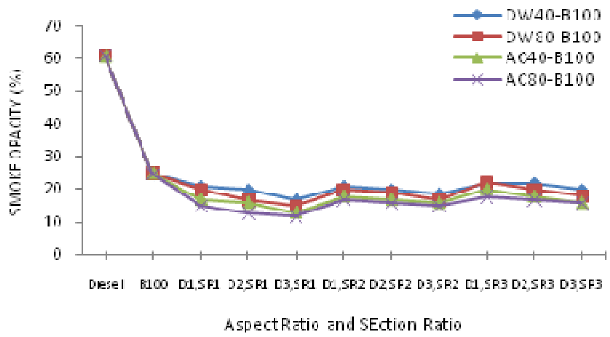

Fig. 22. Effect of section ratio and aspect ratio on smoke emission

Effect on Exhaust Gas Temperature

The results indicated that the exhaust gas temperatures of the preheated pure biodiesel were slightly higher than diesel fuel and unheated biodiesel. The higher exhaust gas temperatures were found for D_3 tube diameter of each section ratio. The slight higher temperatures ranges are observed for SR_1 for both the working fluids and filling ratio. The 80% AC charged HPHXs with D_3 diameter shows around 30 ºC, 11 ºC and 13º C lower EGT for section ratio SR_1, SR_2 and SR_3 respectively at fixed RSQ pattern at full engine load in comparison to 40% AC charged HPHXs. The EGT increases for preheat cause increase of diffused combustion due to high rate of evaporation and improved mixing between methyl ester and air.

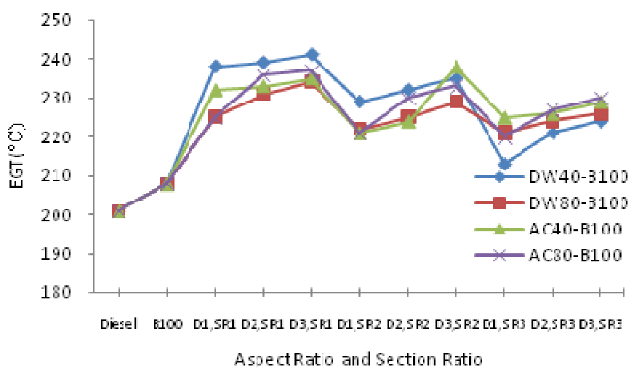

Fig. 23. Effect of section ratio and aspect ratio on Exhaust gas temperature

Effect on EGT drop

The EGT drop at exhaust side of engine is most important parameter regarding engine exhaust. This reduced EGT drop results in reduced exhaust emissions and particulate matters and also reduces the global warming. The Fig.24 shows the variation of EGT dropped by the combined effect of WHR and preheating using HPHXs. The maximum EGT drop is observed for acetone charged HPHXs irrespective of geometrical parameters of HPHXs. The HPHXs with larger tube diameter (D_3) shows the larger drop in EGT. The drop in EGT increased with increased tube diameter from D_1 to D_3. The HPHXs filled with 40% DI shows the lower drop in EGT drop due to lower efficiency of heat extraction from engine exhaust gas.

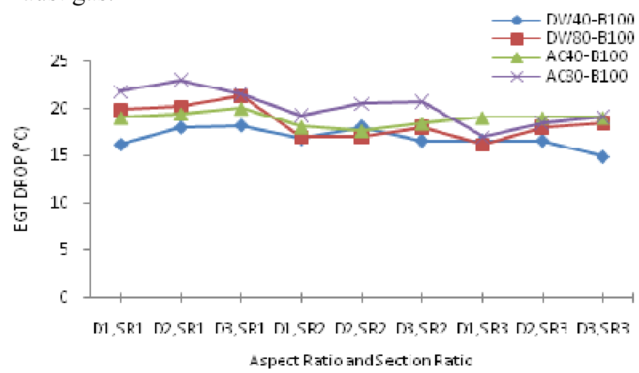

Fig. 24. Effect of section ratio and aspect ratio on EGT drop

Conclusion

The unique HPHXs developed with different geometric and physical variable parameters and assembled to engine at its exhaust side for the recovery of engine exhausted waste heat. The recovered waste heat is utilized for the preheating of pure pongamia biodiesel to improve the engine performance with reduced engine emissions.

The following conclusions were drawn from the experimental results:

- The heat recovered increased with decreased AR and increased tube diameter irrespective of section ratio. The maximum heat recovery of 40.78 W is observed for 80% AC charged HPHXs with D_3 and SR_1.
- The AC 80% HPHX with SR1 shows minimum thermal resistance for all section ratio and aspect ratios. This may be a result of the increased tube diameter and large evaporator length.
- The maximum effectiveness of 0.757 observed for 80% acetone charged HPHXs with SR_1& D_3. The effectiveness of 80% acetone charged HPHXs are nearly 30% higher than DI for all section ratio and aspect ratios.
- The efficiency increases with increased tube diameter and the HPHXs with larger diameter show high efficiency of 41.24%, 34.1% and 29.99% in section ratio SR_1, SR_2 and SR_3 respectively.
- The viscosity reduced with increased heat pipe tube diameter in each section ratio. The HPHXs with D_3 show lowest viscosity of 2.6 cSt almost equal to diesel fuel.
- The 80% acetone charged HPHXs shows the maximum BTE higher than diesel irrespective of aspect ratio and section ratio.
- The CO_2, NO_x and EGT increase with decreasing aspect (increased tube diameter) ratio for each section ratio and the higher values seen for 80 % acetone charged HPHXs for D_3 diameter & section ratio SR_1.

- The maximum EGT drop is observed for acetone charged HPHXs irrespective of geometrical variable parameters (Section ratio and aspect ratio) of HPHXs. The HPHXs with larger tube diameter (D_3) shows the larger drop in EGT.
- The CO, HC and smoke emission reduced with increased tube diameter and the lowest values were noted for 80% acetone charged HPHXs with D_3 & SR_1.

The acetone charge HPHXs shows better results than distilled water under all the section ratio and aspect ratio conditions. By preheating the ignition delay reduced hence the HPHXs with larger diameter and larger evaporator volume shown better results in respect to the performance and emissions.

Acknowledgement

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