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Design of Coil Tube Heat Exchanger for Preheating of Biodiesel

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Abstract—*The present study discuss the use of biodiesel fuel derived from Jatropha oil in a single cylinder direct injection diesel engine blended with commercial diesel fuel with a view to decrease the amount of pollutant and reduce burden on fossil fuels. As the viscosity of biodiesel fuel is high, preheating is done from the exhaust of the engine. For this purpose we have designed a helical coil tube heat exchanger. As the biodiesel is passed through a high temperature zone, heat is exchanged from the surrounding exhaust system, decreasing its viscosity. A separate biodiesel tank is used from which the biodiesel passes through a helical coil tube heat exchanger by the virtue of gravity. The helical coil is wounded on the internal surface of exhaust pipe, and heat from exhaust acts as flue gas that heats the coil and the oil inside by conduction and convection. By performing the calculations, we found out the overall heat transfer coefficient of 55.103 W/m^2 K. Also, the number of turns required to be wounded in the internal surface of the exhaust system was calculated to be 42. It may be summarized from the findings that an alternate for commercial diesel fuel can serve the purpose of driving a diesel engine using this concept of preheating Jatropha oil.*

1. INTRODUCTION

World's energy crisis, global warming, diminishing fossil fuel reserves are raising concerns and inevitability to find more economic and more environmentally friendly solutions to satisfy the current energy consumption. Periodic increase in crude oil prices due to more demand, stringent emission norms, and feared shortages of crude oils due to rapid depletion and net production of carbon dioxide from combustion sources have rekindled interest in renewable vegetable oil fuels [1].

Compression ignition (CI) engines are a major type of Internal Combustion Engines (ICEs). They are commonly known as diesel engines. The higher thermal efficiency of diesel engines has made them popular in applications and is frequently used for power generation. Trucks, buses and earth moving machineries use high speed diesel engines with output ranges varying from 220 kW to 740 kW. In general, diesel engines have an efficiency of about 35% and thus the rest of the input energy is wasted. Despite recent improvements of diesel engine efficiency, a considerable amount of energy is still expelled to the ambient air with the exhaust gas. In water-cooled engines about 25% and 40% [2, 3] of the input energy are wasted in the coolant and exhaust gases, respectively. Johnson [4] found that for a typical 3.0 L engine with a maximum output power of 115 kW, the total waste heat dissipated can vary from 20 kW to as much as 40 kW across the range of usual engine operation. It is suggested that for a typical and representative driving cycle, the average heating power available from waste heat is about 23 kW [2]. Since the wasted energy represents about two-thirds of the input energy and for the sake of a better fuel economy, exhaust gas from diesel engines can be an important heat source that may be used in a number of ways to provide additional power and improve overall engine efficiency. Various techniques are being developed all over the world to use biodiesel in conventional diesel engine.

In this study a thorough review has been done on this kind of techniques. The exhaust heat recovered from a diesel engine is used to preheat bio diesel in order to use it as an alternative for conventional diesel fuel. For this purpose, a helical coil tube heat exchanger is designed. Heat exchangers are widely used in various kinds of application such as power plant, nuclear reactors, refrigeration and air-conditioning systems, heat recovery systems, petrochemical, mechanical, biomedical industries. Energy crisis, global warming, diminishing fossils fuel have made green fuel a suitable alternative for the future, as it is environment friendly and often slight modification in its characteristics makes it similar like conventional diesel fuel.

Biodiesel, a non-petroleum diesel is a mixture of mono-alkyl esters of long chain fatty acid (FAMEs) and it is an alternative fuel obtained from vegetable oils and animal fats. It is a renewable energy, more cleanly than petroleum fuel and have a large availability sources [2-5]. The concern about biodiesel is quickly increased since the petroleum crises in 1970s that cause rapidly increasing in market prices. Growing concern of the environment and the effect of greenhouse gases also had revived more and more interests in the use of vegetable oils as a substitute of petroleum fuel [4, 6]. Biodiesel generally has higher density, viscosity, cloud point, cetane number, lower volatility and heating value compared to diesel fuel that effect on the engine performance and emissions. However, neat biodiesel or its blends may be used in the existing diesel engines with little or no modification to the engine [7-11].

1.1 The Influences of Biodiesel Viscosity on Combustion Process

In the era of improvement technologies, emission regulations have become more stringent in order to keep and maintain clean and healthy environment. Industrial revolution especially in automotive industry was contributing quite higher number of percentage to the earth pollutions in our daily life that consequently will contribute to global warming effects and acid rain formation. Despite years of improvement on the petroleum fuels and combustion characteristics were attempts, issues regarding emissions still become the main conversation in the automotive industry. Thus, demand on the utilization of biodiesel fuels and its blends as alternative energy sources is urgently required to meet the future legislation.

However, lots of researchers have reported [13-17] that use of biodiesel or its blends effects on:

- Fuel droplet formation
- Poor atomization
- Vaporisation
- Air fuel mixing process

These add up due to their higher viscosity.

These effects cause important engine failures such as:

- Fuel filter clogging
- Piston ring sticking
- Injector choking
- Carbon formation deposits
- Rapid deterioration of lubricating oil [14-17]
- High viscosity fuel also leads to high smoke, HC and CO emissions [13]

The present work states all the calculated design parameters and the overall heat transfer coefficient of the heat exchanger. With the available data, computer simulation was carried out to improve the design of the heat exchanger to operate optimally for this particular application.

2. METHODOLOGY

2.1 Selection of Helical Coil Heat Exchanger

Several heat exchangers can be used to recover heat depending on temperature of exhaust gas and its utilization. Helical coil heat exchanger was found to be suitable taking three major factors into consideration:

Firstly, space in exhaust pipe is limited. Secondly, under the condition of laminar flow or low flow rates where a shell and tube heat exchanger would become uneconomical because of the resulting low heat transfer coefficients. Thirdly, the heat transfer coefficient (h) for gases is generally several times lower than that for water, oil and other liquids. Hence, the heat transfer surface for the gas needs to have a much larger area and be more compact to increase the exposure area and residence time for oil. On the coil tube heat exchanger both ends of the

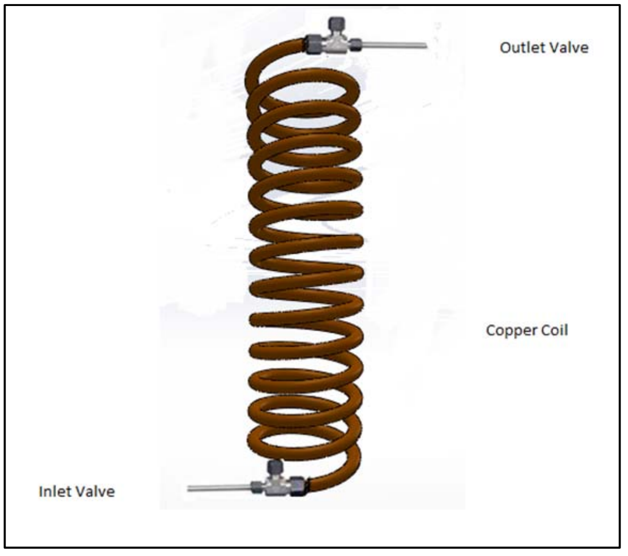

Fig. 1: Showing a coil tube heat exchanger.

coil will have control valves attached, namely, the inlet valve and the outlet valve. Since the viscosity of bio diesel is high and the tube diameter is small, so it would be uneconomical and non-efficient to allow it to flow naturally on the basis of gravity or pressure difference. To overcome this problem, a small pump is used to infuse the biodiesel inside the copper tube to maintain a constant flow of the bio-diesel from the bio-diesel storage tank and we will have to attach pressure regulators and pressure gauges to maintain the required flow rate and to monitor the optimal amount of pressure required to regulate the flow.

The helical coil heat exchanger is fixed on the inner surface of the bend tube section of the exhaust pipe. The bend tube section will be of higher diameter than the other sections of the pipe to ensure that the flow of the exhaust gases is not disturbed.

The outside surface of the bend tube section is insulated to trap maximum heat inside the heat exchanger. The critical radius of insulation is determined from the relation;

$$r = \frac{k}{h} \qquad \text{(A)}$$

Where k= thermal conductivity of the insulating material and H= overall heat transfer coefficient.

Table 1: Technical specification of the engine used for study.

Engine	Single cylinder, direct Injection
Number of valves	2
Displacement	441.5cc
Bore x Stroke	86.0 x 76.0
Compression ratio	20.3:1
Fuel type	Diesel
Maximum Power	6.3kW (9.1 bhp) @3600rpm
Maximum Torque	21.5 Nm@2000-2400 rpm
Transmission Type	4-Speed forward,1 Reverse

2.2 Mathematical relationship used for the design of heat exchanger and the design parameters:

This section deals with the theoretical principles applied for the design of helical coil.

Determination of Heat Transfer Coefficient Outside the coil, h_o

To calculate h_o following parameters must be known:

Diameter of the exhaust pipe, D= 47mm

Diameter of copper tube, d = 4 mm

Diameter of the helix = (47-4-2*2.3) mm=38.4 mm

Thickness of the tube, x = 0.1 mm

Inside diameter = 3.8 mm

Pitch, p = 2 mm

Mass flow rate of exhaust gas can be calculated from the composition of the fuel supply, we have

Taken it as M = 0.0303 kg/s = 109.278 kg/h

M_f= Fuel consumption=0.425 kg/kW h

ρ = Density of Jathropa = 890 kg/m^3

The inlet and outlet temperature of the exhaust is taken as t_{hi} = 300°C and t_{ho} = 250°C (arbitrary)

The inlet and outlet temperature of the bio-diesel is taken as, t_{ci}=30°C and t_{co}= 75°C (arbitrary)

Copper has thermal conductivity, K=400.26 W/mK

=344.16 kcal/hmK

R_a= Shell-side fouling factor = 0.00176 m^2 K W^{-1}

(Anonymous [18])

R_t = Tube-side fouling factor = 0.00053 m^2 K W^{-1}

Length of the coil needed to make N no of turns,

$$L = \sqrt{(Circumference)^2 + (Pitch)^2} \times \text{No of turns} \qquad (1)$$

$$= \sqrt{(\pi * 38.4)^2 + (2)^2} \times N$$

=120.65 N *10^{-3} m

Mass velocity of the exhaust gas,

$$G= \frac{M}{\frac{\pi}{4}\times D^2} \qquad (2)$$

$$= \frac{109.278}{\frac{\pi}{4}\times(0.047)^2} * 10^6$$

=62986.45 kg/m^{2}h

Viscosity of the gas flow can be calculated from,

$$\mu = 51.12 + .372 \times T + 1.05 \times 10^{-4} \times T^2 + 53.147 \times \frac{\%O_2}{100\%} - 74.143 \times \frac{\%H_2O}{100\%} \qquad (3)$$

Where, T = 410 K, O_2 = 10 %, H_2O = 5 %

This gives us:

μ = 222.8989*10^{-6} poise = 222.8989*10^{-6} g cm^{-1}s^{-1}

= 0.08024 kg m^{-1} h^{-1}

Thermal conductivity of gas, K_{gas} = 0.024 W/mK

Reynolds number for the gas,

$$N_{Re} = \frac{D\times G}{\mu} \qquad (4)$$

$$= \frac{.047*62986.45}{0.08024}$$

=36893.86

Prandtl number of the gas can be calculated using,

$$N_{Pr} = \frac{\mu\times C_p}{K} \qquad (5)$$

$$=\frac{2.228*10-2*1.15*103\times1.15*103}{0.024}$$

= 1.0679

For Reynolds no greater than 10000,

$$\frac{h_0 D}{K} = 0.36 {N_{Re}}^{0.55} {N_{Pr}}^{0.33} \qquad (6)$$

h_0=61.046 W/m^{2}K

Determination of Heat Transfer Coefficient Inside the coil, h_{io}

Flow rate of oil inside the coil,

$$q= = \frac{M_f}{\rho} \qquad (7)$$

$= \frac{0.425*6.3}{890}$ (Engine power is 6.3 kW @3600rpm)

= 3.008*10^{-3} m^3/h

Cross-Sectional area of the coil,

$$A_f = \frac{\pi d^2}{4} \qquad (8)$$

$= \frac{\pi*(.004)^2}{4}$ m^2

= 1.256*10^{-5} m^2

Oil velocity inside the coil,

$$u = \frac{q}{A_f}\ldots\ldots \quad (9)$$

$= \frac{3.008*10^{-3}}{1.256*10^{-5}}$

=239.49 m/h

Reynolds no for the oil,

$$N_{Re} = \frac{\rho u d}{\mu} \quad (10)$$

$= \frac{890*239.49*.004}{124.956}$ = 6.8231

(Dynamic viscosity of oil, $\mu = 124.956$ kg m^{-1} h^{-1})

Prandtl number for oil,

$$N_{Pr} = \frac{\mu \times C_p}{K}\ldots.. \quad (11)$$

= 2.36

$$h_i = \frac{0.6 N_{Re}{}^{0.55} N_{Pr}{}^{0.31} K}{d} \quad (12)$$

= 225281.81 W/Km^2

Heat transfer coefficient inside the tube wall,

h_{io}= 225281.81* (3.8/4)

= 214017.72 W/m^2 k

Determination of Overall Heat Transfer Coefficient, U

$$\frac{1}{U} = \frac{1}{h_0} + \frac{1}{h_i} + \frac{x}{K} + R_a + R_t$$

$$= \frac{1}{61.046} + \frac{1}{214017.72} + \frac{.0001}{400.26} + 0.00176 + 0.00053$$

U = 55.103 W/m^2 K

$$LMTD = \frac{\theta_1 - \theta_2}{\ln\frac{\theta_1}{\theta_2}}\ldots\ldots\ldots\ldots\ldots\ldots \quad \ldots\ldots\ldots (13)$$

$$= \frac{(300-30)-(250-75)}{\ln\frac{(300-30)}{(250-75)}}$$

=219.07^{0}C

=492.07 K

Heat load,

$$Q = MC_p\Delta t\ldots\ldots\ldots\ldots \quad . (14)$$

= 0.0303 kg s-1 *1.15 kJ kg-1 K-1 *(300-250) K

=1742.25 W

Required area,

$$A = \frac{Q}{U\Delta t_m} \quad (15)$$

=0.0642 m^2

Determination of Theoretical number of turns of Helical Coil (N)

No of turns,

$$N = \frac{A}{\pi d \times \frac{L}{N}} \quad (16)$$

$$= \frac{0.0642}{\pi \times .004 \times 120.65}$$

= 42.34

=42 (approx.)

3. RESULTS AND DISCUSSION:

3.1 Computerized model

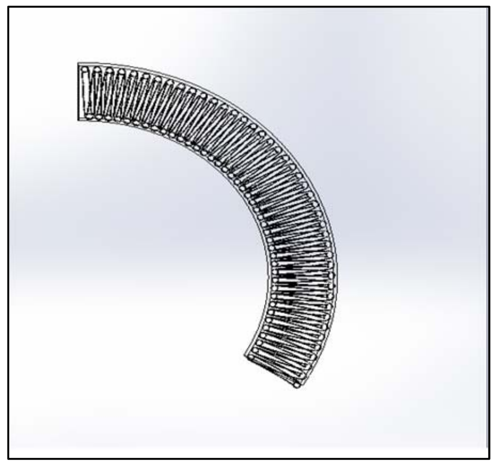

Fig. 2: Wireframe view (front) of midsection of the heat exchanger.

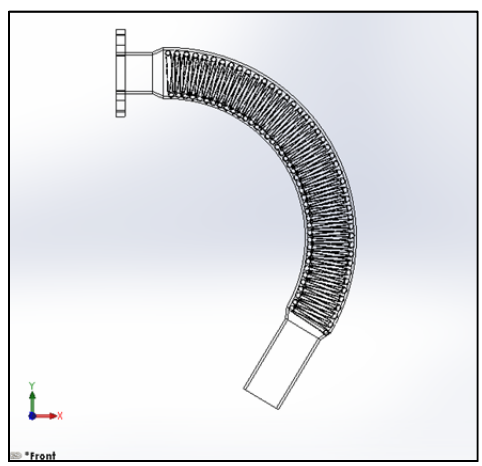

Fig. 3: Wireframe view (front) of the heat exchanger along with the exhaust flange and the tail exhaust.

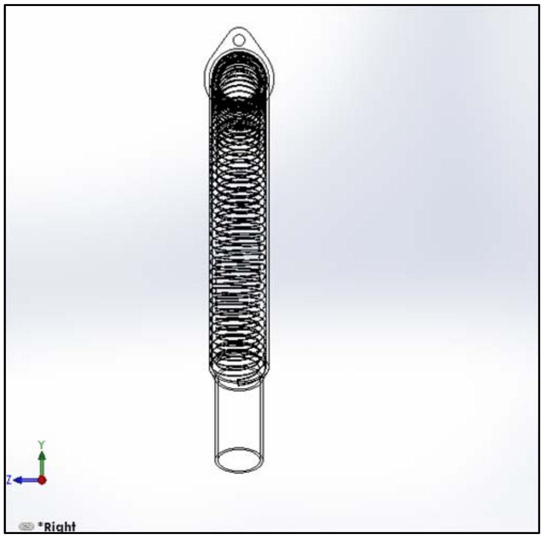

Fig. 4: Wireframe view (right) of the heat exchanger along with the exhaust flange and the tail exhaust.

Table 3: Design parameters

Copper tube diameter	d = 4 mm
Pitch	p = 2 mm
Diameter of the exhaust pipe	D = 47 mm
Length of the coil	L = 5 m
Mass velocity of the exhaust gas,	G = 62986.45 kg/m^2h
Reynolds no for the gas ,	N_{Re}= 36893.86
Prandtl number of the gas,	N_{Pr} =1.0679
Heat transfer coefficient,	h_o= 61.046 W/m^2K
Flow Rate of oil inside the coil,	q=3.008×10^{-3} m^3/h
Cross-Sectional area of the coil,	A_f =12.56×10^{-6} m^2
Oil velocity,	u=0.0665 m/s
Reynolds no for the oil,	N_{Re} =6.8231
Prandtl number for oil ,	N_{Pr}=2.36
LMTD	492.07 K
Heat Load,	Q=1742.25 W
Required area	A=0.0642 m^2
No. of turns= 42	42

4. CONCLUSIONS

- Overall heat transfer coefficient was calculated to be as 55.103 W/m^2 K.
- Total number of turns was calculated to be as 42.

A model of a coil tube heat exchanger is designed on a single cylinder 4 stroke engine. The coil tube was put inside the bent tube section of the exhaust and fixed to the inner surface. The biodiesel preheats to match with the spray characteristics of conventional diesel fuel before combustion. This is a study which leads to the maximization of efficiency through the waste heat recovered from the engine exhaust. This study shows that a lot of factors affect the performance of the heat exchanger with some of them like heat recovered from exhaust, to use the minimum possible space available for better economy and optimum performance. Also with the rising crisis of oil exploration and production, for a sustainable future researches are being conducted to use biodiesel as alternative fuel and along with environment friendly processes to maximize efficiency of the vehicle.

5. ACKNOWLEDGEMENTS

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