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Article

Design and Development of Innovative Protracted-Finned Counter Flow Heat Exchanger (PFCHE) for an Engine WHR and Its Impact on Exhaust Emissions

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Abstract: This article describes and evaluates an Organic Rankine Cycle (ORC) for waste heat recovery system both theoretically as well as experimentally. Based on the thermodynamic analysis of the exhaust gas temperature identified at different locations of the exhaust manifold of an engine, the double-pipe, internally–externally protruded, finned counter flow heat exchanger was innovatively designed and installed in diesel engine for exhaust waste heat recovery (WHR). The tests were conducted to find the performance of heat recovery system by varying the fin geometries of the heat exchanger. The effect of heat exchanger on emission parameters is investigated and presented in this work. The experimental results demonstrated that the amount of heat transfer rate, the effectiveness of heat exchange rand the brake thermal efficiency improved with an increase in length and number of the fins. A significant reduction was observed in all major emissions after the implementation of catalytic-coated, protracted finned counter flow heat exchanger. It also demonstrated the possibility of electric power production using steam turbo-electric-generator setup driven by the recovered exhaust heat energy.

Keywords: waste heat recovery; exhaust steam; heat exchanger; protracted fin; turbo-electric generator; exhaust emissions

1. Introduction

Global energy demand is increasing every day due to excess population, transportation of people and products across the nations, and for industrial purposes. In order to overcome the present deficiency situation, there is a need for effective techniques to leverage the maximum amount of available energy. Improvement in the efficiency of internal combustion engines plays a great hardship for the researchers. A diesel engine utilizes a maximum of 30% from the fuel energy whereas the rest is lost due to cooling and exhaust gases. The engine crankshaft receives less than 30% of the generated energy. About 40% of the fuel energy gets wasted in exhaust gas whereas the remaining amount of heat energy goes unused in cooling system as well as during friction losses [1]. In the present research work, innovative steps have been taken to recover the heat wasted from the engine exhaust gas. Thermo electric generator, turbo-compounding, rankine cycle, Organic Rankine Cycle, gas turbine cycle, exhaust gas recirculation, automotive air conditioning, six stroke engine concept are the different techniques available to utilize engine WHR [2].

Based on the literature review, in order to utilize the waste heat energy available in the exhaust gas, different types of heat exchangers and Organic Rankine Cycles are used. Previous research works mainly focused in harvesting the exhaust heat energy. However, studies related to heat exchanger with innovative heat recovery and simultaneous reduction in emissions were not carried out. This necessitates the invention of novel conceptual design on exhaust heat recovery heat exchanger for the betterment of energy recovery and diesel engine exhaust emission reductions. In the present work, an internally–externally protruded and finned counter flow heat exchanger was designed, fabricated, and experimented in order to utilize the exhaust heat. The waste heat recovered was utilized to generate power using turbo-electric-generator set up and the emission characteristics were also investigated. The current paper discusses about the experimental set up and the methodology to conduct experiments. The PFCHE design and its parametric properties were estimated. The detailed results, discussion regarding the PFCHE-based waste heat recovery and its impact on engine exhaust emissions are discussed in the sections below.

2. Literature Review

In every phase of research and development in WHR, there is a well-defined need exist for exploration and interpretation of the technical literature. The first step in research work is to conduct an extensive review of the related works conducted earlier. The review process comprises of specific information, detailed survey, and preliminary review. This paper reviewed a number of peer-reviewed journal articles to illustrate various fields of hypotheses subjects. A summary of closely-related literature is presented in Table 1.

Table 1. Literature summary of closely related work.

Ref. No.	Authors	Year	Objective and Outcomes
[3]	W Gu et al.	2009	Recovering low and medium-temperature heat (that ranges from 60 °C to 200 °C) from sources which include industrial waste heat, geothermal energy, solar heat, biomass, and so on, is an important sustainable method to solve the energy crisis.
[4]	Borsukiewicz-Gozdur et al.	2007	Organic Rankine Cycle (ORC) systems are feasible for power generation from these low and medium-temperature heat sources. This cycle consists of elements such as boiler, condenser, expander, pump, and working fluid. Organic fluids are more comfortable to work at a low temperature source compared to other fluids.
[5]	Damiana Chinese et al.	2004	The Organic Rankine Cycle boiler receives heat energy from engine exhaust gases and it converts working fluid into steam energy. Steam expands at turbine and produces the mechanical rotation of the output shaft which generates power. The exhaust of the turbine is supplied to a condenser for phase change. Finally, the working fluid gets circulated to boiler for the same kind of repeated operations through the pump.
[6]	Uilli Drescher et al.	2007	A procedure was created to calculate ORC efficiency with sufficient accuracy, based on the design institute for physical properties and also to find appropriate fluids for ORC in biomass power plants.
[7,8]	Rieder de Oliveira Netoetal et al.	2016	A study was conducted upon waste heat energy recovery from internal combustion engines using Organic Rankine Cycle. A technical and economic study was conducted in this work in order to increase the efficiency of electricity production, and thus reduce the fuel consumption as well as emission of polluting gases from internal combustion engines. In order to achieve it, two Organic Rankine Cycle sets were suggested. The first one was facing deployment in water shortage areas (Organic Rankine Cycle using a cooling tower for the condensing system) and another one with water supply condenser made by urban water net. Both simulated systems were able to increase electricity production by almost 20% when toluene was used as working fluid.

Table 1. *Cont.*

Ref. No.	Authors	Year	Objective and Outcomes
[9]	Muhammad Fairuz Remeli et al.	2014	A theoretical model was developed to extract the exhaust waste heat and simultaneous power generation by utilizing a thermo-electric generator and heat pipe. The theoretical system was developed to measure the performance of heat pipes and thermo-electric generator based on heat pipe in numbers, heat input, and air flow rate. The heat transfer rate has reached its maximum level when more rows of heat pipe and thermo-electric generator module were installed. It was concluded that the design was able to recover 10.39 kW of the electrical power and 2 kW of the heat input used to extract 1.35 kW of thermal energy from the engine.
[10]	Mastrullo R et al.	2015	Modelled and optimized a shell and lowered mini-tube heat exchanger for internal combustion engine which was installed with Organic Rankine Cycle. In order to achieve better energy conversion process, heat exchangers were designed with less weight and refrigerant charge. Two engines were installed in order to design and optimize the heat exchanger for waste heat recovery process.
[11]	M. Hatami et al.	2014	Aimed at obtaining a numerical study of the finned type of heat exchangers for waste heat recovery from internal combustion engines. The proposed technique of Hatami et al. used water as the working fluid for compression ignition engines whereas for spark ignition engine, it used water with ethylene glycol as working fluid. In this work, numerical designs were carried out successfully for extracting exhaust heat from internal combustion engines. The discussions were very clear in this study about the impacts on heat recovery due to fin numbers, length, and thickness. The study concluded with improved heat transfer rate and positive energy recovery results.
[12]	Bock Choon Pak et al.	2003	An experimental study was conducted to investigate the effects on air side fouling and cleaning of various condenser coils. The results stated that the amount of dust deposits mostly depends on fin geometry of the heat exchangers.
[13,14]	Chen Bei and H. G. Zhang et al.	2015 2013	A numerical model was established for heat recovery from the exhaust gas of an engine. Engine exhaust gas mass flow rate and exhaust gas temperature values were taken for the analysis from heavy duty diesel truck engine and light duty passenger car engine. It was found that under any working conditions, the efficiency of engine is increased with the combination of Organic Rankine Cycle when compared to original engine performance.
[15,16]	Heng Chen and Yu jin et al.	2015 2013	In their experimental results, it was revealed that the pressure drop increases with the increase of fin height and fin width.
[17]	Songsong Song et al.	2015	Waste heat recovery has great potential in terms of increasing the efficiency and optimizing the fuel consumption. The conservative steam power cycle is applied in general industrial power plants widely; however, the performance of the Rankine cycle is not suitable to tap the energy from low-temperature waste heat source. In order to increase the efficiency and sound economic performance of energy sources, ORC (Organic Rankine Cycle) is used widely to tap low temperature heat sources such as solar energy, geothermal energy and industrial waste heat, and convert it into useful power.

Table 1. *Cont.*

Ref. No.	Authors	Year	Objective and Outcomes
[18]	Marco Altosole et al.	2017	The exhaust heat recovery works on Organic Rankine Cycle concept which is targeted at improving the overall efficiency of the diesel engine.
[19]	Pablo Fernandez-Yanez et al.	2018	Deployed thermoelectric generators to convert thermal energy recovered from exhaust gases to electrical energy.
[20,21]	Pablo Fernandez-Yanez et al.	2018	The experimental investigation was carried out in gasoline and light-duty diesel engines. The possibilities of energy recovery were determined at higher loads with speed and concentric tube heat exchanger. The electric-turbo generators harvested high amount of exhaust energy at high load operating modes. The electric-turbo generator recovered power seven times higher than the thermoelectric generator.

3. Experimental Setup and Methodology

A single cylinder with four stroke, water-cooled, and naturally-aspirated diesel engine was designed to generate 3.7 kW power at 1500 rpm which was utilized for waste heat recovery and emission analysis experiments. The technical specifications of the engine are tabulated in Table 2. Air flow was determined accurately by measuring the pressure drop across a sharp edge orifice of the air surge chamber using U-tube manometer. The diesel flow was measured using a burette arrangement by noting the time of fixed volume of diesel consumed by the engine. A water-cooled piezoelectric pressure transducer was fixed onto the cylinder head to record the pressure variations in cathode-ray oscilloscope screen along with crank angle encoder. The exhaust gas temperature was measured by a chromel–alumel K-type thermocouple. The exhaust gas constituents such as HC, CO, CO_2, and O_2 were measured using an AVL 444N model gas analyzer (Gurgaon, New Delhi, India). NO_x emission was measured using heated vacuum NO_x analyzer (Camberley, Surrey, England) whereas the smoke emission was measured by an AVL smoke meter (Gurgaon, New Delhi, India). Based on the thermodynamic analyses of exhaust gases' temperature at different locations in the exhaust manifold of an engine, the protracted internally–externally finned counter flow heat exchanger was designed and implemented in diesel engine for exhaust heat recovery with water as the working fluid. A schematic representation of the experimental arrangement is shown in the Figure 1. The engine was started using diesel fuel and allowed to warm up. The amount of the injected diesel fuel got automatically varied due to the governor attached to it and this maintained the engine speed at 1500 rpm throughout the experiment. The exhaust heat recovery and emission analysis were performed for different engine loading conditions.

Table 2. Technical specifications of engine.

Description	Type
Engine	Vertical Single Cylinder, Water cooled 4-stroke "Kirloskar Diesel engine"
Rated Power	3.7 kW at 1500 RPM
Bore × Stroke	80 mm × 110 mm
Displacement Volume	553 cc
Compression Ratio	16.5:1
Dynamometer	Rope-Brake Dynamometer
Fuel injection release pressure	200 bar
Specific fuel consumption	40 g/kW·h
Fuel injection timing	27° BTDC
Nozzle	M1CO; DLL110S 1630
Injector type	Mechanical injector
Type of Lubrication	Splash type
Lubricating Oil	SAE30/SAE40
Overall Dimensions	W2000 × D2500 × H1500 mm

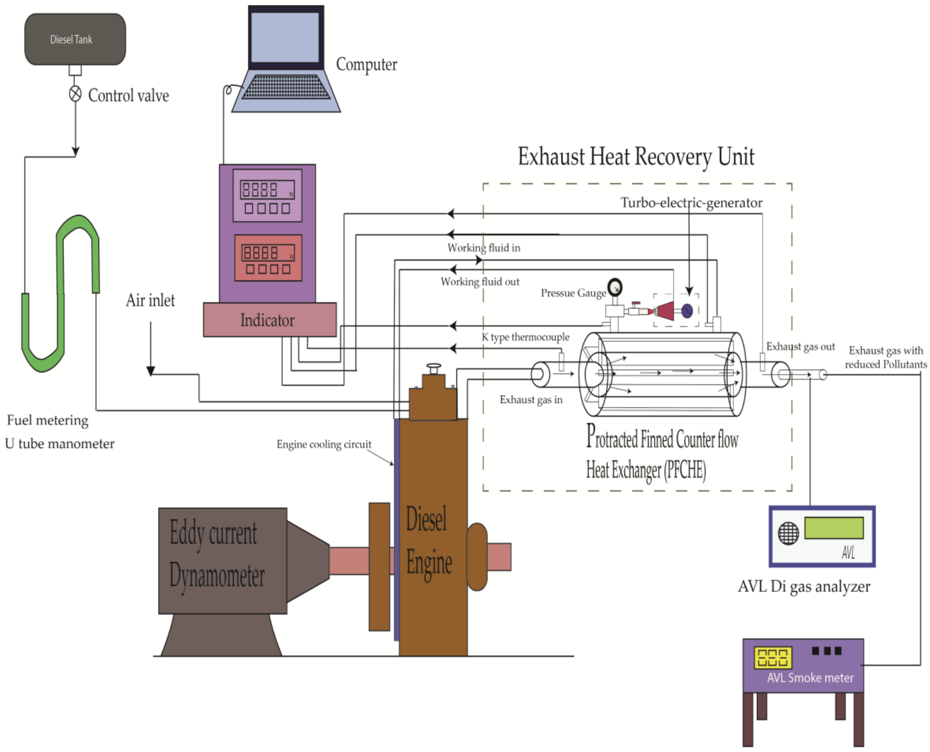

Figure 1. Schematic diagram of experimental setup.

Furthermore, the turbine generator setup was facilitated to examine the efficiency of the heat recovery system. The exhaust gas temperature was measured at different locations in order to locate the heat recovered by the heat exchanger to achieve the maximum effectiveness of heat exchanger which is installed in the diesel engine. As shown in the Figure 2, the exhaust gas temperature decreases as the distance from engine mouth increases. It is mainly due to the loss of heat energy to surroundings with increase in travel distance. At full load condition, the engine acquires more amount of air fuel mixture and thus involves in high rate of combustion which results in higher exhaust gas temperature compared to other engine conditions.

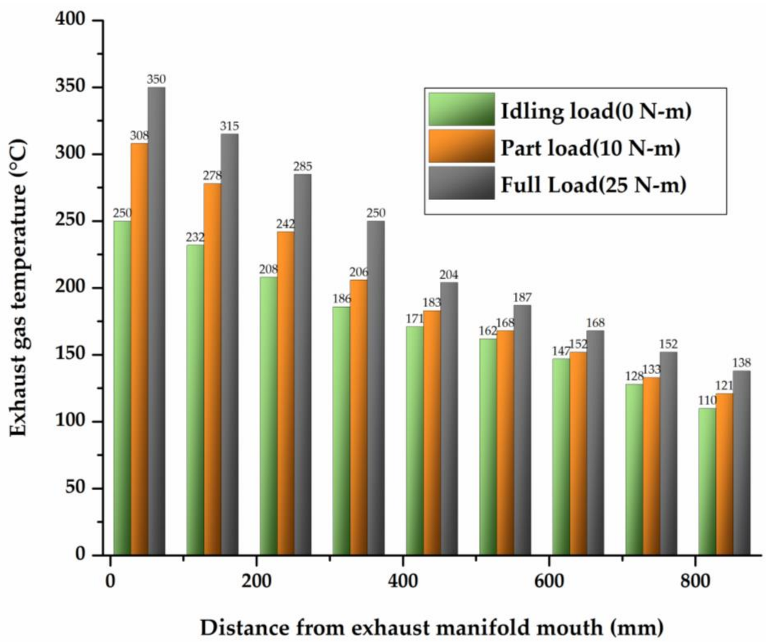

Figure 2. Exhaust gases temperature at different locations.

3.1. Protracted Finned Counter Flow Heat Exchanger Design Parameters

The protracted-finned heat exchanger design is primarily aimed at recovering internal combustion exhaust heat energy. While enumerating the heat exchanger design, the exhaust gas mass flow rate was calculated for a selected diesel engine by adding the mass flow rate of air and fuel for single cylinder diesel engine. The working fluid used in heat exchanger plays a vital role in extracting the heat. The properties of working fluids (i.e., water as cold fluid and engine exhaust gas as hot fluid) are listed in Table 3. Aluminium is selected as the heat exchanger material by considering its favorable thermal conductivity value of 204.4 W/(m·K).

Table 3. Properties of hot and cold fluids.

Input Parameters	Symbols	Hot Fluid (Exhaust Gas)	Symbols	Cold Fluid (Water)	Units
Inlet Temperature	T_{hi}	235	T_{ci}	32	
Outlet Temperature	T_{ho}	124	T_{co}	106	
Thermal Conductivity	K_h	0.0404	K_c	0.6	W/m·K
Specific Heat Capacity	C_{ph}	1030	C_{pc}	4182	J/(kg·K)
Viscosity (Absolute)	μ_h	0.000027	μ_c	0.0006	$(N{\cdot}s)/m^2$
Density	ρ_h	0.696	ρ_c	998	kg/m^3
Mass Flow Rate	m_h	0.009336	m_c	0.0054	kg/s

3.1.1. Convection Heat Transfer Coefficient of Heat Exchanger

The heat transfer coefficient formulates the required length and size of the heat exchanger including developing and fully-developed regions to recover exhaust waste heat energy. Numerous parameters were considered and the data was calculated to find the heat transfer coefficient for inner pipe and the outer pipe of a typical heat exchanger [22]. Table 4 shows the determined values of various parameters which are essential to find out the heat transfer coefficient.

Table 4. Heat transfer calculation parameters for heat exchanger.

Parameters	Symbols	Inner Pipe (i) Hot Fluid (Exhaust Gas)	Symbols	Outer Pipe (a) Cold Fluid (Water)	Units
Velocity of fluid	V_{hi}	4.069	V_{ca}	0.0015	m/s
Fluid Flow Area	A_i	0.00322	A_a	0.0103	m^2
Hydraulic Diameter	D_{hi}	0.064	D_{ha}	0.064	m
Reynolds Number	Re_i	6713.34	Re_a	156.01	-
Prandtl Number	Pr_i	0.68	Pr_a	4.182	-
Friction Factor	f_i	0.0353	f_a	0.41	-
Nusselt Number	Nu_i	19.63	Nu_a	5.49	-
Heat Transfer coefficient	h_i	12.40	h_a	51.47	$W/(m^2{\cdot}K)$

3.1.2. Heat Transfer Surface Area of Protracted Finned Heat Exchanger

The convective heat transfer area has to be calculated in order to determine the heat transfer rate as well as other important thermal parameters. The equations used for different conditions are as follows. If fins are added into exhaust gas (internally–externally) side to promote the boundary layer separation, it enhances the increased heat transfer for this experimental work and the total heat transfer surface area is calculated using the expression as follows

$$A_s = A_{total} = A_{unfinned} + N_f A_{fin} \tag{1}$$

The determined values of the heat transfer area are tabulated in Table 5. The heat exchanger fins' performance parameters like efficiency and effectiveness are getting increased due to its construction material that possess higher thermal conductivity characteristics.

Table 5. Heat transfer surface area of finned heat exchanger.

Description	Symbols	Hot Fluid (Exhaust Gas)	Symbols	Cold Fluid (Water)	Units
Finned Area	A_{fi}	0.54162	A_{fa}	0.54162	m^2
Un finned (Inner pipe) Area	A_{bi}	0.171069	A_{ba}	0.189911	m^2
Total surface Area	A_{ti}	0.71268	A_{ta}	0.731531	m^2

3.1.3. Overallheat Transfer Co-Efficient

The overall heat transfer coefficient is primarily influenced by thickness and thermal conductivity of the media through which heat is getting transferred effectively. The larger the coefficient, the easier heat gets transferred from its source to the working fluid being heated. In a heat exchanger, the overall heat transfer co-efficient (U) for protracted finned double-pipe heat exchanger was calculated using the following equation for the particular design considered [23]. The determined overall co-efficient value was 10.257 $W/(m^2{\cdot}K)$.

$$\frac{1}{UA_s} = R_{total} = \frac{1}{h_i A_i} + \frac{R_{fi}}{A_i} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2\pi Lk} + \frac{R_{fo}}{A_o} + \frac{t_i}{kA_{fi}} + \frac{t_o}{kA_{fo}} + \frac{1}{h_o A_o} \tag{2}$$

3.1.4. Effectiveness of the Designed Finned Heat Exchanger

The effectiveness of the heat exchanger remains the 'performance measuring parameter' of the component which was designed and utilized for the heat recovery. It is the ratio of the actual heat transfer rate for a heat exchanger to the maximum possible heat transfer rate [24].

$$\text{Effectiveness } (\varepsilon) = \frac{Q_{actual}}{Q_{max}} = \frac{C_h(T_{hi} - T_{ho})}{C_{min}(T_{hi} - T_{ci})} = \frac{C_c(T_{co} - T_{ci})}{C_{min}(T_{hi} - T_{ci})} = \frac{1 - e^{-NTU(1-C_r)}}{1 - C_r e^{-NTU(1-c_r)}} \tag{3}$$

In general, it is possible to express effectiveness as a function of Number of Transfer Units, NTU; the heat capacity rate ratio, C_r; and the flow arrangement in the heat exchanger,

$$\text{Number Transfer Unit (NTU)} = \frac{UA_s}{C_{min}} \tag{4}$$

The first dimensionless parameter is nothing but Heat Capacity Ratio, the percentage of the minimum-to-the-maximum value of Heat Capacity Rate for the exhaust gas and water. The heat capacity ratio of a fluid is determination of its capability to liberate or take up heat. This is calculated for both fluids as the product of the mass flow rate times the specific heat capacity of the fluid,

$$\text{Heat capacity ratio } (C_r) = \frac{C_{min}}{C_{max}} \tag{5}$$

By substituting all the determined values in the effectiveness Equation (3), the protracted internally–externally finned counter flow double-pipe heat exchanger effectiveness (ε) in % was calculated as 75.67. The effectiveness of the designed double pipe protracted finned type of heat exchanger shows a considerable improvement when compared with the design carried outfor double pipe heat exchanger without fins [25].

3.1.5. Geometry Design Parameters of Finned Heat Exchanger

Based on the above designed procedure, Table 6 lists out the parameters obtained for the protruded finned counter flow heat exchanger. Without affecting the heat transfer co-efficient, the optimized number of fins were coated with diesel oxidation catalysts so as to reduce the engine emissions. The Figure 3 depict various designed parameters of the heat exchanger. According to the design, the heat exchanger was fabricated and fitted in the diesel engine exhaust manifold.

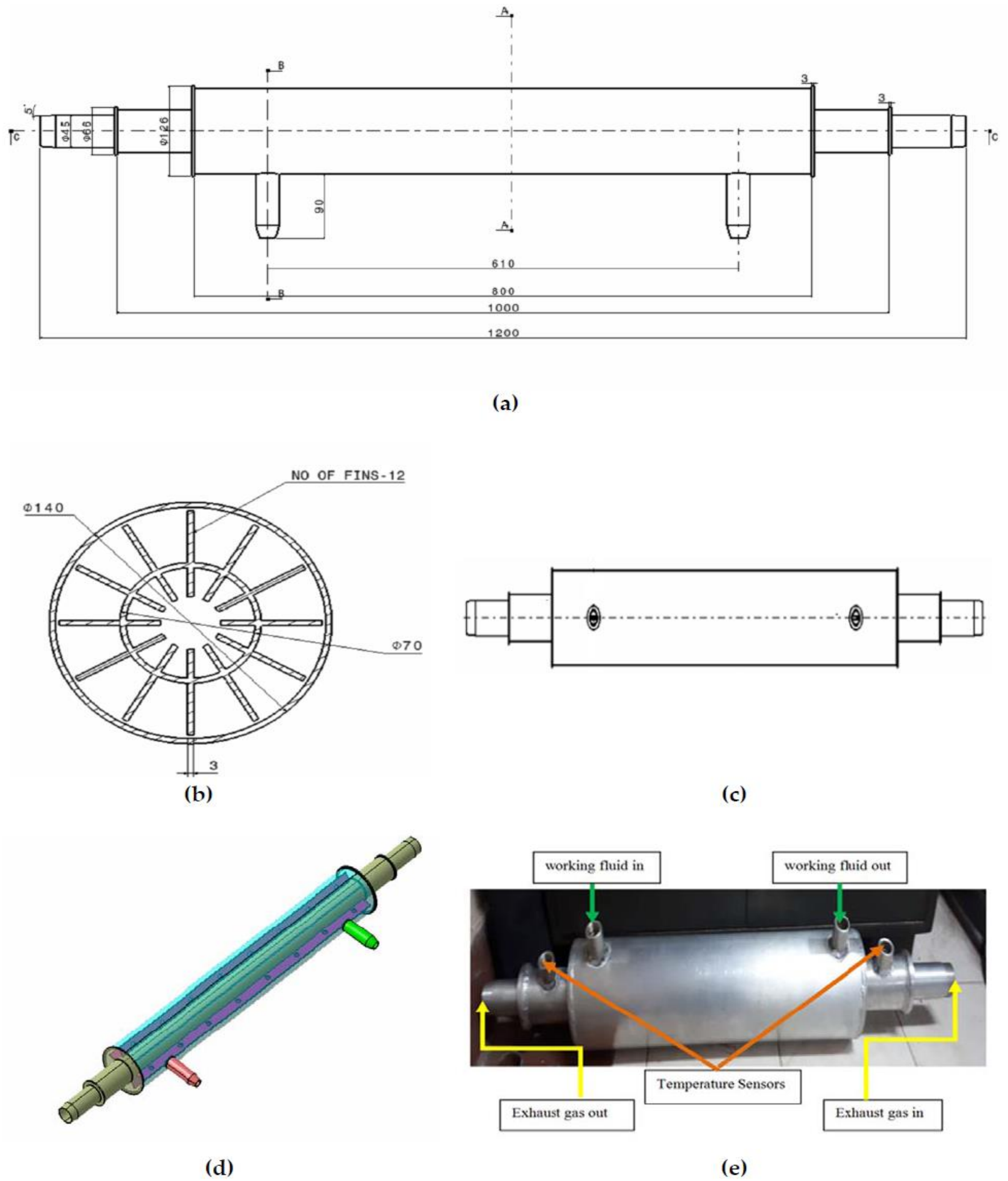

Figure 3. Schematic sketch of 2-Dimensional, 3-Dimensional and fabricated heat exchanger views of PFCHE. (**a**) Front view, (**b**) Side view, (**c**) Top view, (**d**) Isometric view, (**e**) Fabricated view.

Table 6. Dimensions of heat exchanger.

Parameters	Symbols	Inside	Outside	Units
Height	H	0.03	0.03	m
Thickness	T	0.003	0.003	m
Cross section Area	A	0.03	0.03	m^2
Perimeter	P	2.006	2.006	m
Length of fin	L_f	1.0	1.0	m
Number fins	N_f	12	12	-
Finned heat transfer Surface Area Convection	A_f	0.5416	0.5416	m^2
Tube area available for heat transfer in finned tube heat exchanger	A_b	0.17106	0.1899	m^2
Total area of finned tube heat exchanger	A_t	0.7127	0.7315	m^2
Inside diameters of pipes	d_i, D_i	0.064	0.114	m
Outside diameters of pipes	d_o, D_o	0.07	0.12	m

3.2. Error Analysis

Errors and uncertainties are usually unavoidable in any research and it is associated with various primary experimental measurements and the calculations of performance parameters. It can occur during selection of instruments, conditioning, environmental factors, calibration, observation, test planning, and while taking readings. Uncertainty analysis is usually carried out to prove the precision and accuracy of the experiments. Percentage uncertainties of different parameters like performance, emission, and combustion parameters were calculated using the percentage uncertainties of various instruments tabulated in Table 7. The total percentage of uncertainty in this experiment is determined by using an Equation (6)

$$\begin{aligned}\text{Total percentage of uncertainty}\\ &= \{(TFC_{UC})^2 + (BP_{UC})^2 + (SFEC_{UC})^2 + (BTE_{UC})^2 + (CO_{2UC})^2\\ &+ (HC_{UC})^2 + (NOx_{UC})^2 + (Smoke_{UC})^2 + (EGT_{UC})^2 + (PP_{UC})^2 + (\epsilon)^2\\ &+ (HT_{UC})^2 + (PO_{UC})^2\} = \pm 2.61.\end{aligned} \quad (6)$$

Using the appropriate calculation procedure, the total uncertainty for the entire experiment was obtained to be ±2.61%. An uncertainty analysis was carried out using the method put forth by Holman [26,27].

Table 7. List of devices, its range, accuracy, and percentage.

S. Number	Devices	Range	Accuracy	(%) Uncertainty
1	Exhaust gas temperature indicator	0–900 °C	+0.1°C to −0.1°C	+0.15 to −0.15
2	Gas analyzer	CO (0–10%) CO_2 (0–20%) HC (0–10,000 ppm) NO_x (0–5000 ppm)	+0.02% to −0.02% +0.03% to −0.02% +20 ppm to −20 ppm +10 ppm to −10 ppm	+0.2 to −0.2 +0.15 to −0.1 +0.2 to −0.2
3	Smoke level measuring instrument	437C,IP52(0 to 100%)	+0.1 to −0.1	+1 to −1
4	Speed measuring unit	0–10,000 ppm	+10 rpm to −10 rpm	+0.1 to −0.1
5	Burette for fuel measurement	-	+0.1 cm_3 to −0.1 cm_3 +0.6 s to −0.6 s	+1 to −1 +0.2 to −0.2
6	Pressure pickup	-	+1 o to −1 o	+0.2 to −0.2
7	Manometer	0–110 bar	+0.1 kg to −0.1 kg	+0.1 to −0.1

4. Results and Discussion

An innovative PFCHE was designed and fabricated to extract and utilize in the production of useful power output and simultaneously to reduce the engine emissions. The following topics discuss about the performance of PFCHE and emission characteristics of the engine.

4.1. Fin Geometry Effect on Exhaust Gas Outlet Temperature

The effect of fin geometry on exhaust gas temperature is shown in the Figure 4. As shown in the plot, the final temperature of the exhaust gas decreases as the number and length of the fin increases due to high availability of heat transfer surface area. About 57% of the heat was recovered when the number of fins and the fin length of heat exchanger were modified from 6 to 12 and 0.6 m to 1.0 m respectively.

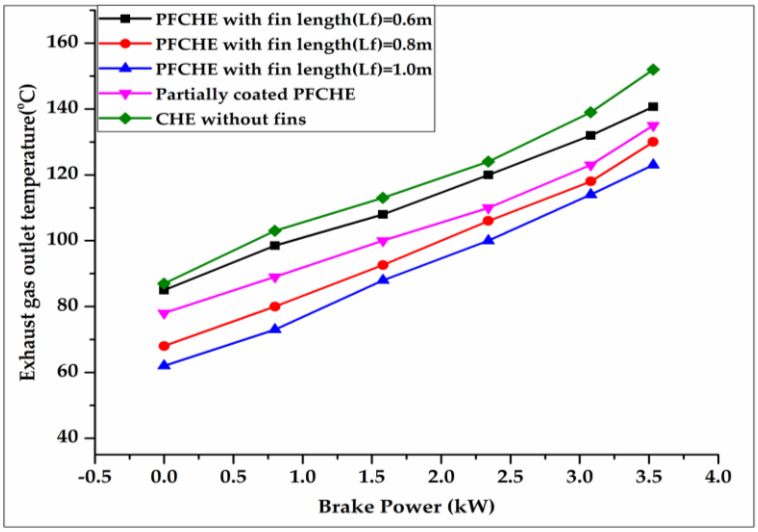

Figure 4. Variation of exhaust gas outlet temperature with fin geometry.

4.2. Energy Recovered by the Working Fluid

The amount of heat absorbed by the working fluid shows an increasing trend with respect to increase in the geometric parameters such as number and length of the fin. As shown in Figure 5, the maximum water outlet temperature was attained when the fin length was 1.0 m with a total of 12 fins. About 37% additional heat absorption was observed, when the fin number and the fin length varied from 6 to 12 and 0.6 m to 1.0 m respectively, due to improved heat transfer area.

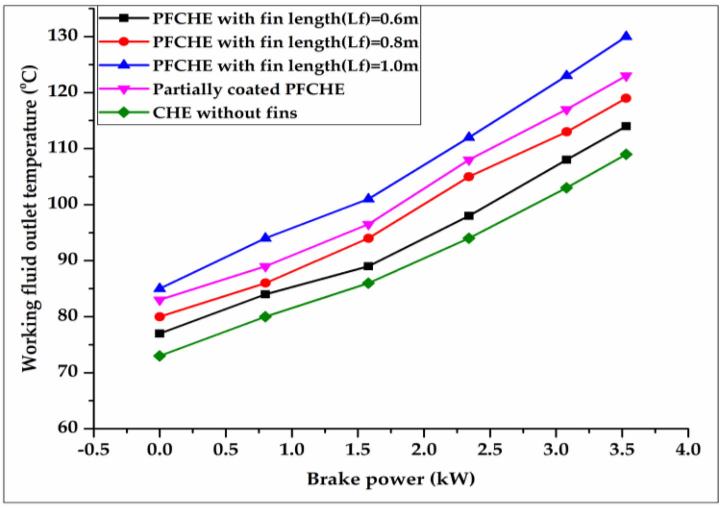

Figure 5. Variation of working fluid outlet temperature with fin geometry.

4.3. Heat Transfer Rate of Working Fluid

Figure 6 shows the variation in heat transfer rate with fin geometry. The rate of heat transfer in the working fluid was determined according to Log-Mean Temperature Difference method (LMTD).

The maximum heat transfer of 550 W was obtained for 1.0 m fin length with 12 fins compared to all other fin geometries. About 39% high amount of heat transfer rate was observed in PFCHE with fin length of 1.0 m when compared with CHE without fins. High heat transfer rate was achieved for 1.0 m fin length when compared with partially-coated heat exchanger. The recovered exhaust energy was used to run the turbine and in-turn the turbo-electric generator. The results showed that this set up can produce 0.06 kW and 0.55 kW of power when the turbine speed is 1500 rpm and 3500 rpm respectively.

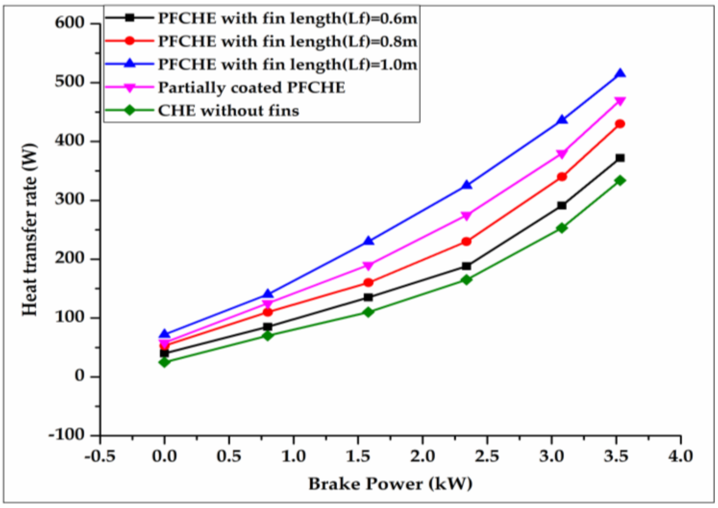

Figure 6. Variation of heat transfer rate with fin geometry.

4.4. Effectiveness of the Heat Exchanger

As the number of fins and length increases, the transfer area also increases due to which the actual heat transfer rate increases which results in the increased effectiveness of heat exchanger. It is evident from the Figure 7, that the effectiveness of heat exchanger increases with increased length and number of fins. The maximum amount of effectiveness, that is, 76%, was found for 1.0 m fin length and 12 fins compared to other fin geometries. The overall performance of the heat exchanger got improved by fin and geometrical configurations of the heat exchanger as advised by Mohd Zeeshan [28].

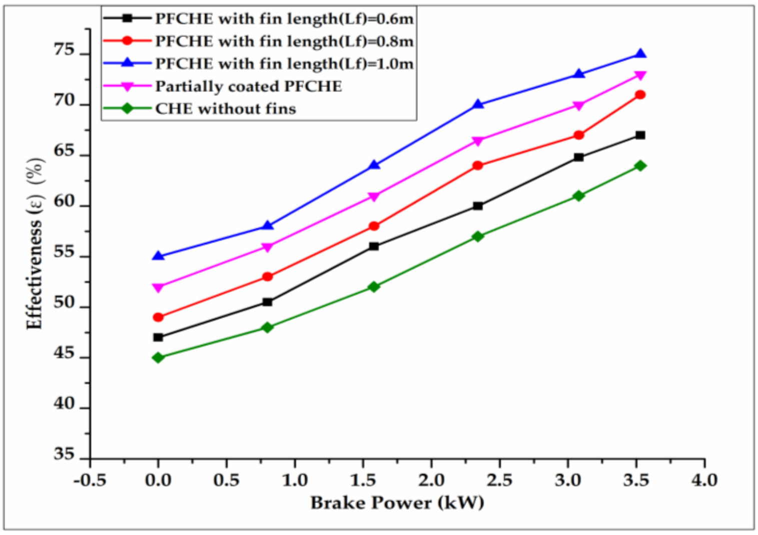

Figure 7. Effectiveness of heat exchanger with fin geometry.

4.5. Brake Thermal Efficiency

The variation of brake thermal efficiency with brake power for different heat exchanger parameters is shown in Figure 8. The brake thermal efficiency was calculated from the ratio of brake power and additional power produced by WHR to the total energy input contributed by the diesel fuel. The brake thermal efficiency in waste heat recovery technique at full load is found to be 37% at PFCHE without coating, 34.5% at heat exchanger without fins, 36% at partially coated PCFHE. It was observed that the overall brake thermal efficiency increased about 5% by utilizing the waste heat energy recovered from the exhaust gas.

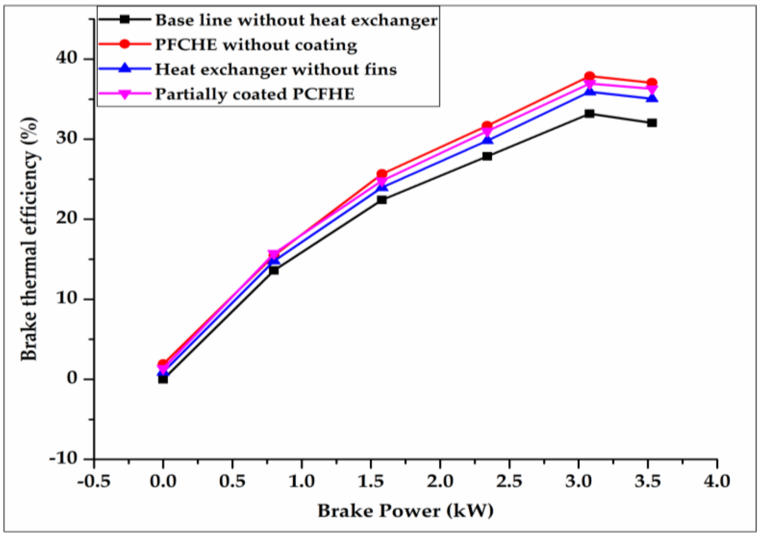

Figure 8. Effect of waste heat recovery (WHR) on brake thermal efficiency.

4.6. Engine Emission Parameters

4.6.1. Hydro Carbons

Hydrocarbon emission is the emission of a combination of unburned fuels due to low temperature that occurs near the cylinder wall. Hydrocarbons consists of thousands of species such as alkanes, alkenes, and aromatics. Diesel engines normally release low levels of hydrocarbons compared to petrol engines. The impact of heat exchanger on hydrocarbon emission is shown in Figure 9. As shown in the plot, there is a significant increase in hydrocarbon when brake power was increased. The hydrocarbon emission was comparatively higher when the emission test was conducted without finned heat exchanger set up, whereas it was lower when the emission test was conducted with finned heat exchanger. The partially-coated finned heat exchanger resulted in reduced hydro carbon level due to oxidation effect [29].

4.6.2. Carbon Monoxide

Carbon monoxide emission mainly occurs due to incomplete combustion of air and fuel. Particularly, it can be caused at beginning as well as at instantaneous acceleration of engine during which the rich mixtures are required. In rich air–fuel mixtures, due to air shortage and reactant concentration, all the carbon cannot be converted into CO_2 due to which CO is produced. Figure 10 depicts the comparison of CO emission from an engine exhaust 'with finned' and 'without finned' the use of heat exchanger. When the test was conducted without installing finned heat exchanger, CO was highly emitted than when using heat exchanger with fins. With the protracted finned heat exchanger, carbon monoxide emissions started to reduce at high load conditions due to lattice oxygen donation from the diesel oxidation catalyst and its reaction with exhaust gases [30].

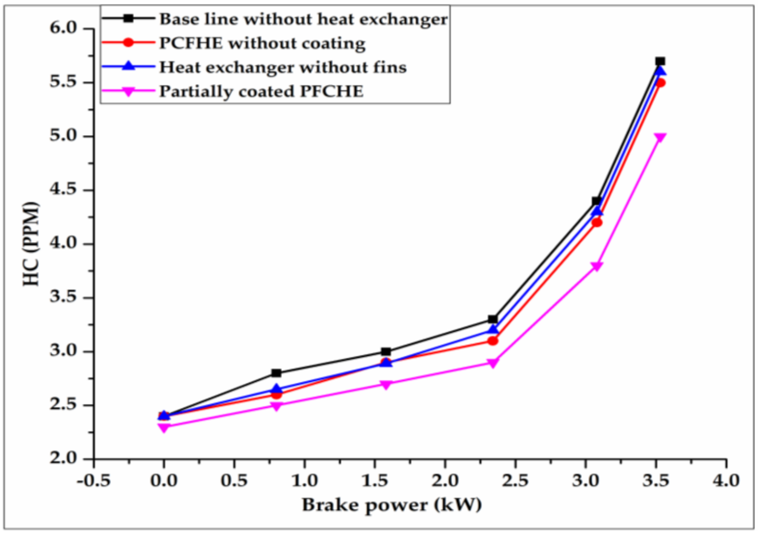

Figure 9. Effect of heat exchanger on HC emission.

4.6.3. Nitrogen Oxides

Nitrogen oxides are known as nitrogen monoxide (NO) and nitrogen dioxide (NO_2). NO constitutes about 85–95% of NO_x. Figure 11 shows the comparison of NO_x emission variations in the experimentation conducted between 'with finned heat exchanger' and 'without finned heat exchanger'. Heat exchanger-based heat recovery technique can reduce considerable amount of NO_x emission when compared with experimental results retrieved from 'without using fins' in the heat exchanger. This reduction might be due to the recovery of thermal energy from exhaust gases and the reaction of exhaust gases with oxidation catalyst used in heat exchanger fins [31].

4.6.4. Carbon Dioxide

The variation of carbon dioxide emission in the exhaust manifold using heat exchanger is plotted in the Figure 12. It shows that there is a slight increase in CO_2 emission when using PFCHE in the diesel engine exhaust compared to heat exchanger without using fins. Waste heat recovery system and its design allow to reduce half of the CO_2 emissions in the diesel engines, when compared to other techniques [32]. It may be due to the oxidation effect of the catalysts used in the PFCHE.

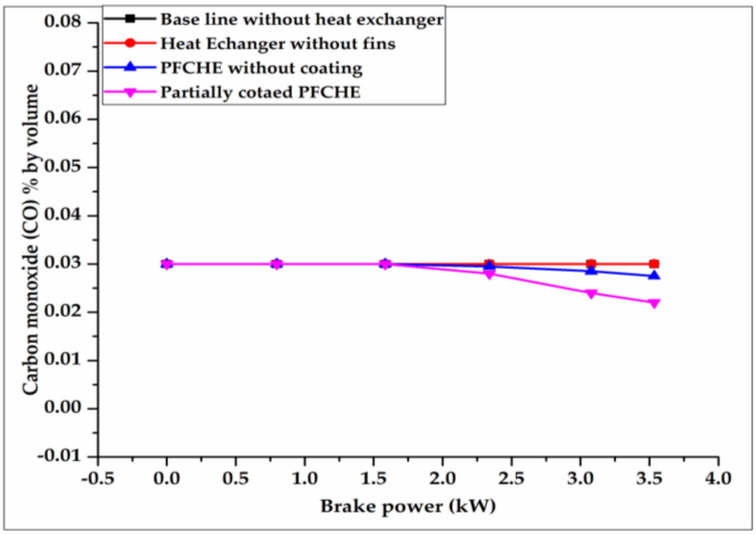

Figure 10. Effect of heat exchanger on CO emission.

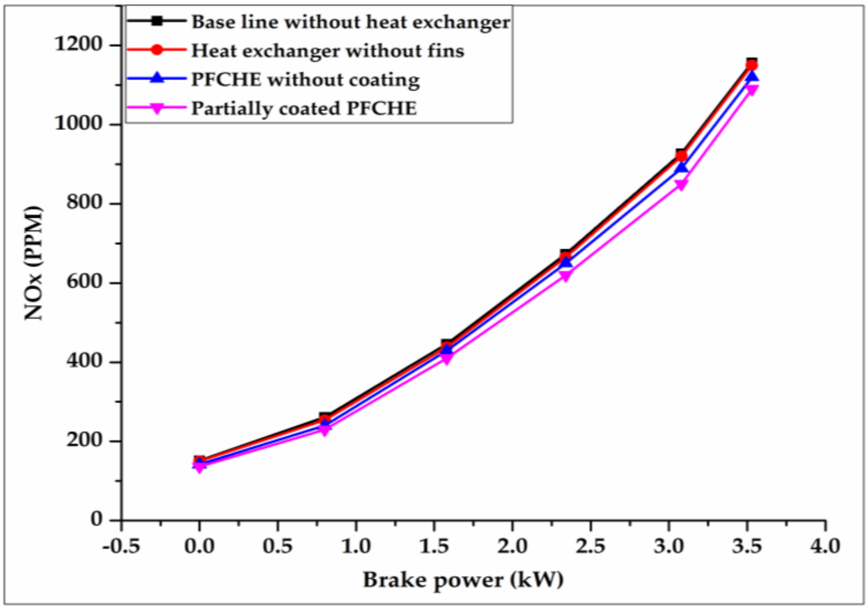

Figure 11. Effect of heat exchanger on NO_x emission.

4.6.5. Smoke Intensity

The comparative results of smoke intensity is indicated as Hatridge Smoke Units (HSU)and is shown in Figure 13. Variation of smoke emissions is relatively less at low power operations due to a smaller amount of fuel particle being present in the burning process. The impact of the implementation of 'protracted both internally–externally finned counter flow heat exchanger with partial coating' in waste heat recovery resulted in low smoke emissions when compared with diesel fuel. This is due to the diesel oxidation catalyst used in part of the heat exchanger fins and reactions with exhaust gases. The smoke was formed due to pyrolysis of PAH (Polycyclic Aromatic Hydrocarbons) and it predominated at full load operating conditions [33].

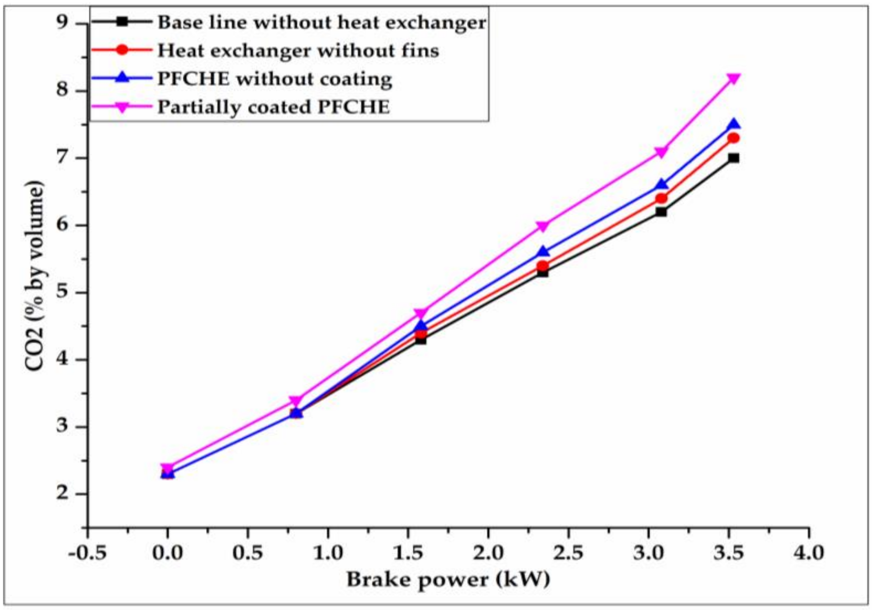

Figure 12. Effect of heat exchanger on CO_2 emission.

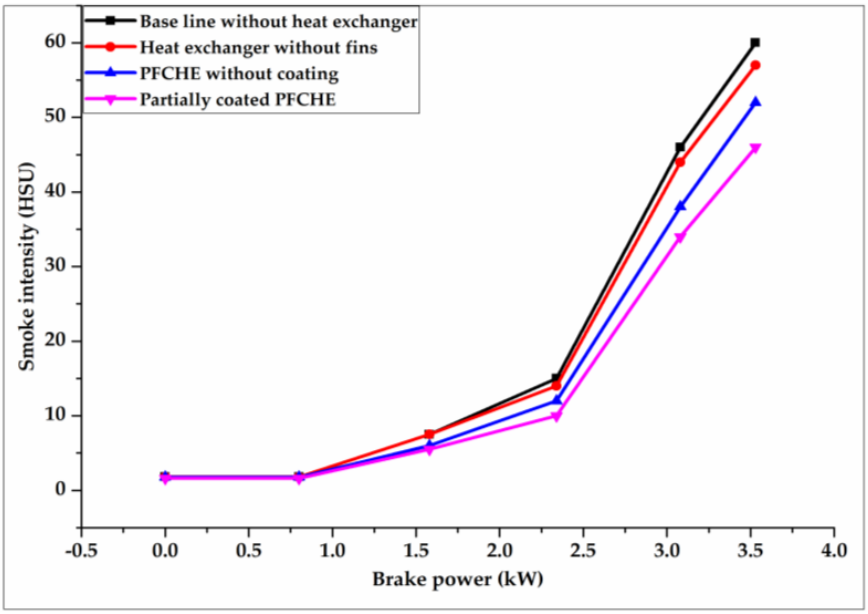

Figure 13. Effect of heat exchanger on smoke intensity.

5. Conclusions

In internal combustion engines (ICEs), About 70% of the heat energy produced by pistons is lost due to the exhaust and cooling process. In this study, an innovative double-pipe, both internally–externally PFCHE was designed and adopted to recover the heat from engine exhaust gas and in parallel, it was also aimed at reducing the harmful exhaust emissions. The following conclusions can be drawn from the experimental results.

- The analytical results indicated a positive notion about the overall efficiency of Organic Rankine Cycle heat recovery system. The experimental results demonstrated that from the heat exchanger without fins, the amount of heat extracted was 335 W. With innovative finned heat exchanger, the amount of heat recovered was 550 W. High amount of heat transfer was achieved, namely, 39%, when the fin length varied from 0.6 m to 1.0 m and when the number of fins were increased from 6 to 12.
- By comparison, the effectiveness of the PFCHE was able to reach its full load operation from 71% to 75%. The effectiveness of the heat exchanger without fins was 10–13% lesser than that of the effectiveness with 1.0 m length finned heat exchanger. It was also revealed that, as the fin numbers and its length increases, the heat transfer rate increases which further resulted in improved performance of the heat recovery system and increased brake thermal efficiency from 32% to 37%.The developed heat recovery system can produce 0.06 kW and 0.55 kW of power when the turbines execute at 1500 rpm and 3500 rpm respectively.
- The application of partially-coated, protracted, and finned heat exchanger showed a considerable reduction in the engine emissions due to diesel oxidation catalysts coating. A reduction in HC, CO and NO_x emissions was observed with partially coated PFCHE. The reduction in HC and NO_x emissions at full load were 16% and 7% respectively when compared to base line engine operation without heat exchanger. Smoke got decreased from 60 HSU to 45 HSU at full load operation of the engine. The reduction could be attributed due to the properties of material used for heat exchanger and exhaust gas reactions.

On the whole, it can be concluded that DOC-coated PFCHE resulted in increase in the heat transfer rate, effectiveness and brake thermal efficiency when compared to the heat exchanger without fins. HC, CO, NO_x and smoke emissions were less than the base line engine operation without heat exchanger. As per the current study results, it is found that the partially-coated PFCHE could be a suitable heat exchanger to recover exhaust heat energy and can reduce engine exhaust emissions. In future, the area of research has to be explored in depth towards the integration of engine coolant heat and exhaust using various power plant cycles. It should also focus on performance improvement under different working fluids that can make better use of a low temperature exhaust heat recovery system and minimize the installation cost along with the size of WHR system.

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Nomenclatures

ρ	fluid density (kg/m^3)
A_s	heat transfer surface area (m^2)
U	overall heat transfer coefficient (W/m^2·K)
Q	rate of heat transfer (W)
Q_{actual}	actual heat transfer (W)
Q_{max}	maximum possible heat transfer (W)
D	cylinder bore (m)
L	stroke length (m)
N	engine speed (rpm)
m_a	mass flow rate of air (kg/s)
m_f	mass flow rate of fuel (kg/s)
C_p	specific heat capacity (J/kg·K)
μ	viscosity (N·s/m^2)
d_i	inner pipe inside diameter (m)
d_o	inner pipe outside diameter (m)
V_h & V_c	velocity of hot and cold fluids (m/s)
K_h & K_c	thermal conductivity of hot and cold fluids (m/s)
T_{hi} & T_{ci}	inlet temperature of hot and cold fluids (K)
T_{ho} & T_{co}	outlet temperature hot, cold fluids (K)
Re	Reynolds number
Pr_i	Prandtl number
Nu	Nusselt number
f	friction factor
h	convection heat transfer co-efficient (W/m^2·K)
D_h	hydraulic diameter (m)
Nf	number of fins
H	height of fin (m)
T	thickness of fin (m)
A	fin cross section area (m^2)
P	perimeter of fin (m)
L_f	length of fin (m)
A_f	finned surface area for heat transfer (m^2)
A_b	un-finned area of pipe (m^2)
A_t	total area of finned tube heat exchanger (m^2)

R_{total}	total thermal resistance $(m^2{\cdot}K/W)$
$R_{fi}\&R_{fo}$	fouling factors of inner pipe and outer pipe $(m^2{\cdot}K/W)$
R_{wall}	resistance of wall $(m^2{\cdot}K/W)$
C_c	heat capacity of cold fluid $(J/kg{\cdot}K)$
C_h	heat capacity of hot fluid $(J/kg{\cdot}K)$
C_r	heat capacity ratio
ε	effectiveness of heat exchanger
Acronyms	
ICEs	internal combustion engines
WHR	waste heat recovery
TEG	turbo electric generator
ORC	organic rankine cycle
PFCHE	protracted finned counter flow heat exchanger
CHE	counter flow heat exchanger
LMTD	log mean temperature difference
NTU	number of transfer units
EGT	exhaust gas temperature
HT	heat transfer
BP	brake power
PP	pressure pickup
PO	power output
BTE	brake thermal efficiency
HC	hydro carbons
CO	carbon monoxide
NO_x	nitrogen oxides
CO_2	carbon-di-oxide
HSU	hatridge smoke units
PAH	polycyclic aromatic hydrocarbons
DOC	diesel oxidation catalysts

References

1. Hatami, M.; Gannji, D.D.; Gorji-Bandpy, M. A review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery. *Renew. Sustain. Energy Rev.* **2014**, *37*, 168–181. [CrossRef]
2. Zhang, Z.; Li, L. Investigation of In-Cylinder Steam Injection in a Turbocharged Diesel Engine for Waste Heat Recovery and NOx Emission Control. *Energies* **2018**, *11*, 936. [CrossRef]
3. Gu, W.; Weng, Y.; Wang, Y.; Zheng, B. Theoretical and experimental investigation of an organic Rankine cycle for a waste heat recovery system. *Proc. Inst. Mech. Eng. Part A J. Power Energy* **2009**, *223*, JPE725. [CrossRef]
4. Borsukiewicz-Gozdur, A.; Nowak, W. Maximizing the working fluid flow as a way of increasing power output of geothermal power plant. *Appl. Therm. Eng.* **2007**, *27*, 2074–2078. [CrossRef]
5. Chinese, D.; Meneghetti, A.; Nardin, G. Diffused introduction of organic Rankine cycle for biomass-based power generation in an industrial district: A systems analysis. *Int. J. Energy Res.* **2004**, *28*, 1003–1021. [CrossRef]
6. Drescher, U.; Brüggemann, D. Fluid selection for the organic Rankine cycle (ORC) in biomass power and heat plants. *Appl. Therm. Eng.* **2007**, *27*, 223–228. [CrossRef]
7. De Oliveira Neto, R.; Sotomonte, C.A.R.; Coronado, C.J.; Nascimento, M.A. Technical and economic analyses of waste heat energy recovery from internal combustion engines by the Organic Rankine Cycle. *Energy Convers. Manag.* **2016**, *129*, 168–179. [CrossRef]
8. Li, L.; Ge, Y.T.; Tassoua, S.A. Experimental study on a small-scale R245fa organic Rankine cycle system for low-grade thermal energy recovery. *Energy Procedia* **2017**, *105*, 1827–1832. [CrossRef]
9. Remeli, M.F.; Tan, L.; Date, A.; Singh, B.; Akbarzadeh, A. Simultaneous power generation and heat recovery using a heat pipe assisted thermoelectric generator system. *Energy Convers. Manag.* **2015**, *91*, 110–119. [CrossRef]

10. Mastrullo, R.; Mauro, A.W.; Revellin, R.; Viscito, L. Modeling and optimization of a shell and louvered fin mini-tubes heat exchanger in an ORC powered by an internal combustion engine. *Energy Convers. Manag.* **2015**, *10*, 697–712. [CrossRef]
11. Hatami, M.; Ganji, D.D.; Gorji-Bandpy, M. Numerical study of finned type heat exchangers for ICEs exhaust waste heat recovery. *Case Stud. Therm. Eng.* **2014**, *4*, 53–64. [CrossRef]
12. Pak, B.C.; Baek, B.J.; Groll, E.A. Impacts of fouling and cleaning on the performance of plate fin and spine fin heat exchangers. *KSME Int. J.* **2003**, *17*, 1801–1811. [CrossRef]
13. Bei, C.; Zhang, H.; Yang, F.; Song, S.; Wang, E.; Liu, H.; Chang, Y.; Wang, H.; Yang, K. Performance analysis of an evaporator for a diesel engine—Organic Rankine Cycle (ORC) combined system and influence of pressure drop on the diesel engine operating characteristics. *Energies* **2015**, *8*, 5488–5515. [CrossRef]
14. Zhang, H.G.; Wang, E.H.; Fan, B.Y. Heat transfer analysis of a finned-tube evaporator for an engine exhaust heat recovery. *Energy Convers. Manag.* **2013**, *65*, 438–447. [CrossRef]
15. Chen, H.; Wang, Y.; Zhao, Q.; Ma, H.; Li, Y.; Chen, Z. Experimental investigation of heat transfer and pressure drop characteristics of H-type finned tube banks. *Energies* **2014**, *7*, 7094–7104. [CrossRef]
16. Jin, Y.; Tang, G.-H.; He, Y.-L.; Tao, W.-Q. Parametric study and field synergy principle analysis of H-type finned tube bank with 10 rows. *Int. J. Heat Mass Transf.* **2013**, *60*, 241–251. [CrossRef]
17. Song, S.; Zhang, H.; Lou, Z.; Yang, F.; Yang, K.; Wang, H.; Bei, C.; Chang, Y.; Yao, B. Performance analysis of exhaust waste heat recovery system for stationary CNG engine based on organic Rankine cycle. *Appl. Therm. Eng.* **2015**, *76*, 301–309. [CrossRef]
18. Altosole, M.; Benvenuto, G.; Campora, U.; Laviola, M.; Trucco, A. Waste heat recovery from marine gas turbines and diesel engines. *Energies* **2017**, *10*, 718. [CrossRef]
19. Fernández-Yañez, P.; Armas, O.; Capetillo, A.; Martínez-Martínez, S. Thermal analysis of a thermoelectric generator for light-duty diesel engines. *Appl. Energy* **2018**, *226*, 690–702. [CrossRef]
20. Fernandez-Yanez, P.; Gomez, A.; García-Contreras, R.; Armas, O. Evaluating thermoelectric modules in diesel exhaust systems: Potential under urban and extra-urban driving conditions. *J. Clean. Prod.* **2018**, *182*, 107–1079. [CrossRef]
21. Fernández-Yáñez, P.; Armas, O.; Kiwan, R.; Stefanopoulou, A.G.; Boehman, A.L. A thermoelectric generator in exhaust systems of spark-ignition and compression-ignition engines. A comparison with an electric turbo-generator. *Appl. Energy* **2018**, *229*, 80–87. [CrossRef]
22. Raei, B.; Shahraki, F.; Jamialahmadi, M.; Peyghambarzadeh, S.M. Different methods to calculate heat transfer coefficient in a double-tube heat exchanger. A. comparative study. *Exp. Heat Transf.* **2018**, *31*, 32–46. [CrossRef]
23. Shah, R.K.; Sekulic, D.P. *Fundamentals of Heat Exchanger Design*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2003. [CrossRef]
24. Navarro, H.A.; Cabezas-Gómez, L.C. Effectiveness-NTU computation with a mathematical model for cross-flow heat exchangers. *Braz. J. Chem. Eng.* **2007**, *24*, 509–521. [CrossRef]
25. Rajesh, R.; Senthilkumar, P.; Mohanraj, K. Design of heat exchanger for exhaust heat recovery of a single cylinder compression ignition engine. *J. Eng. Sci. Technol.* **2018**, *13*, 2153–2165.
26. Holman, J.B. *Experimental Techniques for Engineers*; McGraw Hill Publications: New York, NY, USA, 2003.
27. Lakshmanan, T.; Nagarajan, G. Experimental investigation on dual fuel operation of acetylene in a DI diesel engine. *Fuel Process. Technol.* **2010**, *91*, 496–503. [CrossRef]
28. Zeeshan, M.; Nath, S.; Bhanja, D. Numerical study to predict optimal configuration of fin and tube compact heat exchanger with various tube shapes and spatial arrangements. *Energy Convers. Manag.* **2017**, *148*, 737–752. [CrossRef]
29. Amanatidis, S.; Ntziachristos, L.; Giechaskiel, B.; Samaras, Z.; Bergmann, A. Evaluation of an oxidation catalyst ("catalytic stripper") in eliminating volatile material from combustion aerosol. *J. Aerosol Sci.* **2013**, *57*, 144–155. [CrossRef]
30. Hung, T.C.; Shai, T.Y.; Wang, S.K. A review of organic rankine cycles (ORCs) for the recovery of low-grade waste heat. *Energy* **1997**, *22*, 661–667. [CrossRef]
31. Muthiya, S.J.; Pachamuthu, S. Electrochemical NO_x reduction and oxidation of HC and PM emissions from biodiesel fuelled diesel engines using electrochemically activated cell. *Int. J. Green Energy* **2018**, *15*, 314–324. [CrossRef]

32. Nanthagopal, K.; Ashok, B.; Varatharajan, V.; Anand, V.; Kumar, R.D. Study on the effect of exhaust gas-based fuel preheating device on ethanol–diesel blends operation in a compression ignition engine. *Clean Technol. Environ. Policy* **2017**, *19*, 2379–2392. [CrossRef]
33. Weidemann, E.; Buss, W.; Edo, M.; Mašek, O.; Jansson, S. Influence of pyrolysis temperature and production unit on formation of selected PAHs, oxy-PAHs, N.-PACs, PCDDs, and PCDFs in biochar—A screening study. *Environ. Sci. Pollut. Res.* **2018**, *25*, 3933–3940. [CrossRef] [PubMed]