

# Experimental Investigation of Waste Heat Recovery from Exhaust of Four-Stroke Diesel Engine Using Specifically Manufactured Heat Exchanger



Ram Thakar, Santosh Bhosle and Subhash Lahane

**Abstract** This paper is concerned with means for performance improvement and reducing exhaust emissions of four-stroke single-cylinder diesel engines by heating inlet air passed to the cylinder by using specifically designed and manufactured heat exchanger. A diesel generating set having a cylinder, 5 horse power (HP), water cooled, Kirloskar Make diesel engine was selected as base engine and the experiments were conducted at part load conditions. The diesel generating setup was modified to run with incorporation of heat exchanger and blower. The exhaust heat is used by specifically designed heat exchanger to heat inlet air passed to the cylinder. The blower is used to increase the volumetric efficiency of the engine which tends to reduce due to heating of the inlet air passed to the cylinder. The experiments were conducted for three setups viz. i. Basic diesel engine setup, ii. Modified setup with heat exchanger and iii. Modified setup with heat exchanger and blower. The experimental results obtained with incorporation of waste heat recovery system were compared with base line data. The rectangular-type shell and tube heat exchanger is designed based on the potential heat savings available at the diesel engine exhaust and manufactured. The due attention is paid while selecting the material for manufacturing heat exchanger. The shell is made of cold-rolled carbon steel and tubes used were copper tubes. The results indicate improved performance and reduced emission levels for modified engine, i.e. using specifically designed heat exchanger for heating the inlet air passed to the engine. The results obtained indicate that there is potential in the exhaust gases and heat of exhaust gases can be utilized using specifically designed and manufactured rectangular-type shell and tube heat exchanger to heat inlet air passed to the engine cylinder.

**Keywords** Diesel engine · Exhaust heat recovery · Heat exchanger

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## 1 Introduction

Efficiency is major parameter related to any diesel engine which is always measured for checking its performance. There are many losses concerned with diesel generating (DG) set that tends to reduce the performance of the engine. Among all losses, the exhaust gas loss or exhaust flue gas loss contribute major loss that badly affects on the performance of the engine. The high temperature available in the exhaust gases attributes toward the decline in performance and increasing the exhaust emissions of the engine. Many techniques had been tried to make use of this exhaust heat of gases for improving efficiency and minimizing the emission level.

Abd-Alla investigated on the use of exhaust gas recirculation (EGR) technique to check its potential of recovering exhaust heat from engine exhaust and reducing the  $\text{NO}_x$  emissions. They suggested to make optimum use of EGR by using it in airflow path rather than displacing part of inlet air. The use of EGR by this method substantially reduces  $\text{NO}_x$  emissions [1]. Shi et al. made use of both internal and exhaust gas recirculation on HCCI engine and found reduction in  $\text{NO}_x$  and smoke emissions due to use of homogeneous charged compression ignition system [2]. Hountals et al. verified effect of using cooled EGR gas temperature on turbocharged DI heavy duty diesel engine using multizone combustion model and shown its positive effect on brake-specific fuel consumption and lowering the soot values [3]. Aranguren et al. experimented, validated and developed computational model for thermoelectric generation which predicts results with an accuracy of 12% [4]. Many other researchers investigated on diesel engine with biodiesel blend with diesel fuel. They used waste rice **bran** oil, vegetable cooking oil, pongamia, Pungam methyl esters to prepare biodiesels [5]. In recent years, the new technique of preparation of homogeneous charged compression ignition (HCCI) is becoming familiar where homogeneous charge is prepared by mixing fuel and air which is compressed and allowed to self-ignite [6]. The organic Rankine cycle (ORC) is proven technique to recover low grade heat at 90 °C from industrial excess heat. Lemmens and Lecompte investigation suggested practical and financial suitability of using ORC systems for flue gas heat recovery for electricity generation under certain conditions [7]. The researchers investigated on different technologies for recovery of the exhaust heat from IC Engines. The techniques such as thermoelectric generation, bottoming Rankine cycle, six-stroke cycle found opportunities for potential energy savings and improvement in the performance [8]. Yang et al. designed organic Rankine cycle having low-temperature and high-temperature loops. They used R245fa as refrigerant which extracts heat from coolant and released heat from turbocharged air to recover waste heat from six cylinder diesel engine. The experimentation resulted into an increase in efficiency by 13%. It is also seen there is maximum reduction of 4% in brake specific fuel consumption when diesel engine working in the part of higher load [9]. The new technique introduces the concept of use of light weight material and alternative refrigerant for heat exchangers considering their environmental concerns. Mastrullo et al. optimized geometrical model for a shell and louvered fin mini-tubes heat exchanger with organic Rankine cycles (ORCs) and suggested

low-weight and compact-size heat exchanger to be used for producing considerable amount of work and thermal efficiency [10]. Many researchers investigated to use organic Rankine cycle (ORC) for recovery of exhaust heat and emphasized that the design of evaporator is critical and the success of recovery system entirely depends on its design. Zhang et al. developed mathematical model of evaporator based on its designed dimensions and specified ORC working conditions for exhaust waste heat recovery from diesel engine. They showed as speed and load increase, evaporator outlet exhaust temperature increases. To achieve this, careful selection of heat transfer area for finned tube is required which is based on engine's operating range [11]. Hossian and Bari experimented for waste heat recovery on 40 kW DG set using two of the shelf-type heat exchangers for superheated steam generation. They simulated design of heat exchanger with available data after experimentation and compared it with effectiveness of optimized heat exchanger. They reported less effectiveness of heat exchanger compared to optimized heat exchanger. It is also observed that effectiveness was more for parallel arrangement [12]. Researchers have been trying to improve thermal efficiency of diesel engines by applying different techniques. The effect of high injection pressure and cylindrical air pressure have been investigated on combustion and heat release rate for DI diesel engines shown improved brake thermal efficiency [13]. Bari and Hossain designed and simulated pancake-shaped type heat exchanger by using CFD software and concluded generating additional power of 10.5 kW due to pancake-shaped heat exchanger as compared to heat exchanger of round-shaped-type which was able to produce power 9.5 kW [14]. Meng et al. shown fuel consumption efficiency can be improved by using thermoelectric generators by developing multiphysics model applied in a automobile exhaust wherein exhaust is modeled and reported improvement in system performance at the cost of less thermoelectric material consumption [15]. Kim et al. experimentally investigated on a direct contact thermoelectric generator (DCTEG) for recovery of heat from exhaust of diesel engine to improve performance. They adopted the method of varying coolant temperature, engine load and rotation speed during experimentation. Their result showed improved energy conversion efficiency of DCTEG which was in between 1 and 2%. Their results also show that maximum thermal energy is extracted by DCTEG and about 20% energy wasted to the environment irrespective of load conditions [16]. Shixue et al. used thermoelectric generator (TEG) for recovery of heat from gasoline engine exhaust for which they optimized geometrically sandwich heat exchanger of plate type using finite element analysis and suggested key parameters flow velocity and TEG module area for optimization of TEG [17]. Thakar et al. designed counter flow shell and tube heat exchanger and reported heating of inlet air up to 150 °C [18]. The present paper is the result of experimentation on single cylinder, four-stroke diesel engine with the incorporation of waste heat recovery with use of specifically designed and manufactured heat exchanger and blower. The rectangular-type counter flow shell and tube heat exchanger is designed based on the potential heat savings available at the diesel engine exhaust and then manufactured. The due attention is paid while selecting the material for manufacturing heat exchanger. The shell is made of cold-rolled carbon steel and tubes used were copper tubes. The use of CRC sheet for shell and copper material for tube acts as

thermal storage and heat exchanging device. The result shows substantial savings in the exhaust heat and thereby showing improved performance and reduction in emissions of the engine by waste heat recovery using the heat exchanger between outlet and inlet duct of the diesel engine.

## 2 Experimentation, Instrumentation and Methodology

The present experimentation is completed on vertical, water cooled, single cylinder, four stroke, vertical, 5 HP, diesel engine. The fuel used for experimentation is high speed (HS) diesel oil. The designed heat exchanger is manufactured with attention to recover maximum heat potential from exhaust gas of diesel engine. The details of the material used for manufacturing of heat exchanger are given in Table 1. The modified experimental setup with manufactured heat exchanger is shown in Fig. 1.

Thermocouples connected to control panels are used to measure the temperatures at various locations. The volumetric type of method is used for measuring the fuel consumption. Hartridge smokemeter is used for measurement of smoke in the exhaust. Following three trials were conducted to determine volumetric efficiency, brake thermal efficiency, brake-specific fuel consumption and smoke density. The three experimentations have been conducted on stationary diesel for measurement of the performance and emissions of the engine viz. i: Experimentation on basic diesel engine running at normal conditions at injection timing  $26^\circ$  BEFORE TDC at atmospheric temperature, ii. Experimentation with modified engine setup with heat exchanger at injection timing  $23^\circ$  BEFORE TDC and iii. Experimentation with modified engine setup with heat exchanger and blower at injection timing  $23^\circ$  BEFORE TDC.

**Table 1** Details of material used for manufacturing heat exchanger

Description	Quantity	Material
1. Tubes: O.D = 9.54 mm, I.D = 9.94 mm, length = 4.2 m	14	Copper
2. Shell: (For end closure) Width = 105 m, height = 90 mm, thickness = 2 mm	2	Carbon rolled carbon steel (CRC)
Shell: (For end connectors) Top width = 110 mm, base width = 60 mm, height = 90 mm thickness = 2 mm	8	
3. Baffles: Width = 92 mm, height = 90 mm, thickness = 2 mm	4	Carbon rolled carbon steel (CRC)



Fig. 1 Modified experimental setup with heat exchanger

### ***2.1 Experimental Trial 1: Experimentation on Basic Diesel Engine Running at Normal Conditions at Injection Timing 26° BEFORE TDC at Atmospheric Temperature***

Initially, the cooling water supply is started. The engine allowed to run on no load till steady state has been reached. At no load, the cooling flow rate is adjusted. After the steady state has been reached, the time for outlet water temperature, manometer reading is noted. The exhaust gas sample drawn in smoke meter is analyzed for measuring the percent smoke density. Then, the engine is loaded in step of six, twelve, eighteen and twenty kilograms and the procedure is repeated again.

### ***2.2 Experimental Trial 2: Experimentation with Modified Engine Setup with Heat Exchanger at Injection Timing 23° BEFORE TDC***

The heat exchanger on the basis of availability of heat potential at the exhaust was designed and manufactured. This heat exchanger was placed just near the inlet and outlet ducts of the engine. The inlet air was passed through rectangular shell tube type heat exchanger. In this, the inlet air was passed through the number of tubes and the exhaust gases were passed over these tubes. Efficiencies and emissions of stationary diesel engine for experimentation with modified engine setup with heat exchanger at injection timing 23° BTDC were evaluated. The trial on diesel engine with heat exchanger is conducted at no load to gradually increasing to full load.

### ***2.3 Experimental Trial 3: Experimentation with Modified Engine Setup with Heat Exchanger and Blower at Injection Timing 23° BEFORE TDC***

In this, the blower was placed between the air box and heat exchanger. Proper care was taken for the placement, since the blower is driven by pulley which is driven by camshaft of the engine. Efficiencies and emissions of stationary diesel engine for experimentation with modified engine setup with heat exchanger and blower at injection timing 23° BTDC were evaluated. The trial on diesel engine with heat exchanger and blower is conducted at no load to gradually increasing to full load.

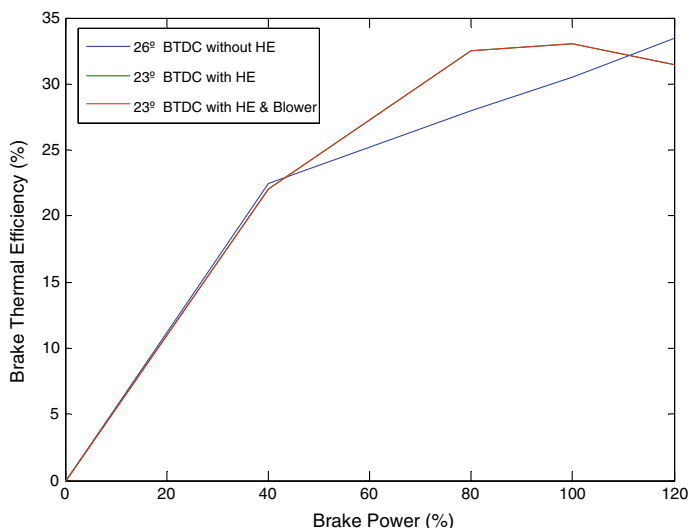
## **3 Results and Discussion**

The performance of 3.7 kW capacity four-stroke single-cylinder stationary diesel engine was evaluated for inlet air temperature 30 °C and injection timing 26° before TDC. The rectangular-type counter flow shell and tube heat exchanger were fabricated and placed upstream of inlet and outlet duct of the engine. In this, inlet air is passed through tubes and the exhaust gases are passed over the tubes. The previous work reports inlet air heating up to 150 °C at the injection timings 23°, before TDC yields best engine performance. The test conducted on same diesel engine with modified engine setup with heat exchanger shows the temperature of air gradually raises with load. At no load, inlet air heating achieved upto temperature of 100 °C when exhaust temperature was 190 °C. At 50% load, inlet air heating achieved upto temperature of 145 °C when exhaust temperature was 235 °C.

The improved performance in terms of thermal efficiency of engine found for setup with heat exchanger is due to heating of inlet air using heat of exhaust gases which also lowers the emission level of the engine. The various performance parameters and emissions of the engine for these three kinds of experimentation were measured and the effect of these experimentation on the performance parameters and emissions of the engine elaborated in details in the following section.

### ***3.1 Thermal Efficiency***

The brake thermal efficiency variations for the three experimental setups at different outputs are shown in Fig. 2. The graph plotted for brake thermal efficiency verses percentage brake power for engine operating at (i) normal condition, (ii) with heat exchanger and (iii) with heat exchanger and blower. The thermal efficiency increases during early part of brake power and it reaches to maximum during full load condition. The trend of decrease in thermal efficiency is observed beyond full load for the engine running at normal conditions. The similar trend is observed for engine operating with

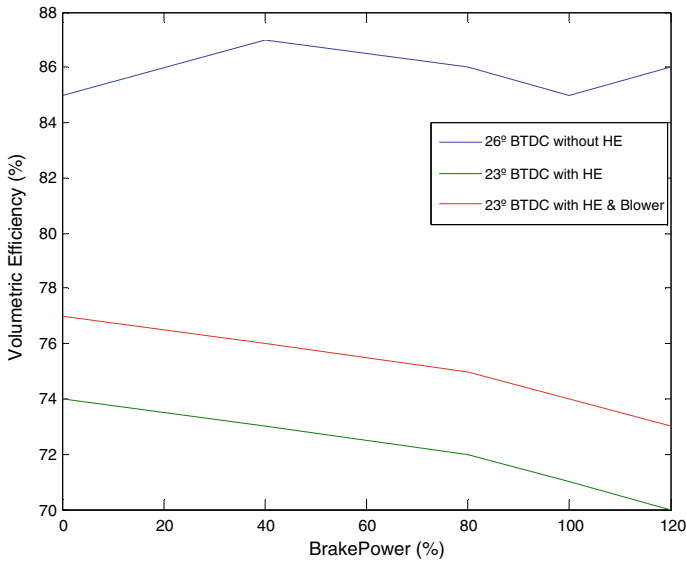


**Fig. 2** Comparison of brake thermal efficiency for three engine setups

heat exchanger where at full load thermal efficiency reaches to maximum value and it **starts** decreasing when engine is operating beyond full load. This is the effect of inlet air heating which improves the engine combustion resulted into improvement in the performance when engine is running at full load. The same effect of inlet air heating does not observed when the engine is running beyond full load and it shows decline in the performance beyond full load. The increase in inlet air temperature helps in proper mixing of fuel at full load which benefited in vaporization and combustion of injected fuel. The values of brake thermal efficiencies at full load and at 120% load are 32.5 and 28.9, respectively. There is no change observed in thermal efficiency when blower is connected to the heat exchanger. The gain in performance in terms of thermal efficiency is lesser as compared to the power consumed by the blower. Due to this no change in thermal efficiency is observed after connecting the blower.

### 3.2 Volumetric Efficiency

The variation volumetric efficiency verses percentage of brake power at various operating conditions shown in Fig. 3 for engine operating at (i) normal condition, (ii) with heat exchanger and (iii) with heat exchanger and blower. The graph shows volumetric efficiency remains more or less same with respect to load for engine running at normal condition. The volumetric efficiency variation for normal engine lies between 84 and 85%. The graph also indicates that the engine running with heat exchanger shows decrease in volumetric efficiency as the load increases. This is due to the arrangement of heating inlet air by heat exchanger tends to reduce the volumetric



**Fig. 3** Comparison of volumetric efficiency for three engine setups

efficiencies as compared to values of efficiencies obtained for engine running with basic experimental setup. This is due to decrease in density of inlet air passed to the engine. After connecting blower to the heat exchanger, the values of volumetric efficiency are found to be increased than the heat exchanger without blower. The loss in volumetric efficiency due to heating of inlet air can be compensated with use of blower.

### 3.3 Brake Specific Fuel Consumption

The effect of brake power on brake-specific fuel consumption (BSFC) at 50, 100 and 110% of brake power calculated and plotted as shown in Fig. 4. The BSFC values corresponding to these load are 0.335, 0.2625, 0.25 kg/kW h, respectively, for engine running at normal conditions. This show reduced values of BSFC as there is increase in load on engine. The graph for engine operating with heat exchanger clearly show that the BSFC is improved for test compared to normal operating conditions. This is due to improved combustion temperature as the temperature of inlet air passed is more than the temperature of inlet air operating under normal operating condition. The values of BSFC obtained for this test are 0.34, 0.2542, 0.25 and 0.2650 kg/kW h at 50, 75, 100 and 110% of brake power, respectively. These values also show that BSFC with heat exchanger is better compared to the normal operating condition between 0.3738 and 0.2650. There is no significant change in BSFC with additional blower.



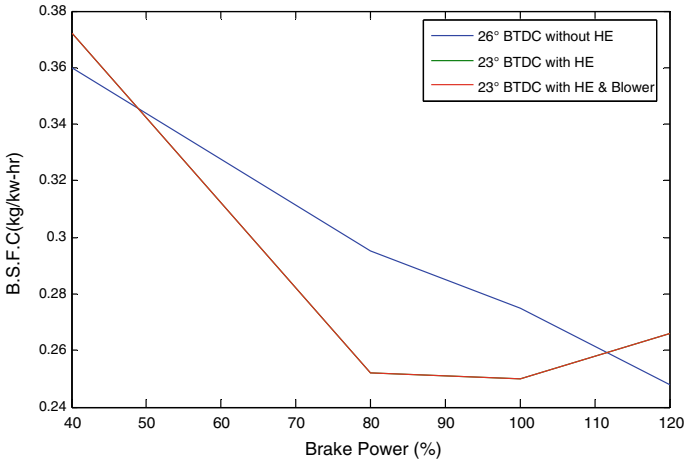


Fig. 4 Comparison of brake specific fuel consumption for three engine setups

### 3.4 Smoke Density

A comparison of the percentage of smoke density from the diesel engine setup equipped with heat exchanger and blower are presented in Fig. 5. The smoke density values measured were 15 and 29% at full load and at overload conditions, respectively, for basic engine setup running at normal conditions. There is reduction in smoke density values to 14 and 22% at full load and overload conditions, respectively, for

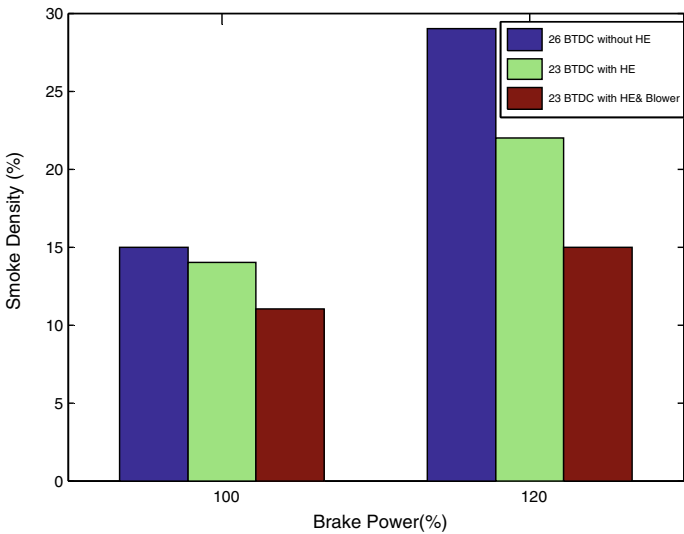


Fig. 5 Comparison of smoke density for three engine setups

modified experimental setup heat exchanger at injection timing of  $23^\circ$  before TDC. It shows that inlet air heating lowers down the emission level of the stationary diesel engine. It is also seen that use of the blower in the suction line further reduces the emission level. There is 6.66% reduction in the smoke density at full load by inlet air heating and 26.66% reduction in smoke density at full load with inlet air heating assisted by blower. Similarly, reduction in smoke density is observed at part load and overload with modified engine setup with heat exchanger and blower.

## 4 Conclusions

The experimentation on diesel engine with technique of using specifically manufactured heat exchanger for exhaust heat recovery has shown improved performance of the engine due to inlet air heating. Performance improvement is depicted by improved values of thermal efficiency. The decrease in volumetric efficiency due to heating of inlet air is compensated by use of blower. It is also seen that specific fuel consumption value improves by inlet air heating and it lowers down the emission level of the stationary engine.

## References

1. Abd-Alla, G.H.: Using exhaust gas recirculation in internal combustion engine: a review. *Energy Convers. Manage.* **43**, 1027–1042 (2002)
2. Shi, L., Cui, Y., Deng, K., Peng, H., Chen, Y.: Study of low emission homogeneous charge compression ignition (HCCI) engine using combined internal and external exhaust gas recirculation (EGR). *Energy* **31**, 2665–2676 (2006)
3. Hountals, D.T., Mavropoulos, G.C., Binder, K.B.: Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions. *Energy* **33**, 272–283 (2008)
4. Aranguren, P., Araiz, M., Astrain, D., Martinez, A.: Thermoelectric generators for waste heat harvesting: a computational and experimental approach. *Energy Convers. Manage.* **148**, 680–691 (2012)
5. Ghobadian, B., Rahimi, H., Nikbakht, A.M., Najafi, G., Yusaf, T.Y.: Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network. *Renew. Energy* **34**, 976–982 (2009)
6. Swami Nathan, S., Mallikarjuna, J.M., Ramesh, A.: Effects of charge temperature and exhaust gas re-circulation on combustion and emission characteristics of an acetylene fuelled HCCI engine. *Fuel* **89**, 515–521 (2010)
7. Lemmens, S., Lecompte, S.: Case study of an organic Rankine cycle applied for excess heat recovery: technical, economical and policy matters. *Energy Convers. Manage.* **138**, 670–685 (2012)
8. Saidur, R., Rezaei, M., Muzammil, W.K., Hassan, M.H., Paria, S., Hasanuzzaman, M.: Technologies to recover exhaust heat from internal combustion engines. *Renew. Sustain. Energy Rev.* **16**, 5649–5659 (2012)
9. Yang, F., Dong, X., Zhang, H., Wang, Z., Yang, K., Zhang, J., Wang, E., Liu, H., Zhao, G.: Performance analysis of waste heat recovery with a dual loop organic Rankine cycle (ORC)

- system for diesel engine under various operating conditions. *Energy Convers. Manage.* **80**, 243–255 (2014)
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. Manage.* **101**, 697–712 (2015)
  11. Zhang, H.G., Wang, E.H., Fan, B.Y.: Heat transfer analysis of a finned tube evaporator for engine exhaust heat recovery. *Energy Convers. Manage.* **65**, 438–447 (2013)
  12. Hossian, S.N., Bari, S.: Waste heat recovery from the exhaust of a diesel generator using Rankine cycle. *Energy Convers. Manage.* **75**, 141–151 (2013)
  13. Yuksek, L., Sandalci, T., Ozener, O., Ergenc, A.T.: Modelling the effect of injection pressure on heat release parameters and nitrogen oxides in direct injection diesel engines. *Therm. Sci.* **18**, 155–168 (2014)
  14. Bari, S., Hossain, S.N.: Design and optimization of compact heat exchanger to be retrofitted into a vehicle for waste heat recovery from a diesel engine. *Procedia Eng.* **105**, 472–479 (2015)
  15. Meng, J.-H., Wang, X.-D., Chen, W.-H.: Performance investigation and design optimization of a thermoelectric generator applied in automobile exhaust waste heat recovery. *Energy Convers. Manage.* **120**, 71–80 (2016)
  16. Kim, T.Y., Negash, A., Cho, G.: Experimental and numerical study of waste heat recovery characteristics of direct contact thermoelectric generator. *Energy Convers. Manage.* **140**, 273–280 (2017)
  17. He, W., Wang, S., Yang, Y.: Peak power evaluation and optimal dimension design of exhaust heat exchanger for different gas parameters in automobile thermoelectric generator. *Energy Convers. Manage.* **151**, 661–669 (2017)
  18. Thakar, R., Bhosle, S., Lahane, S.: Design of heat exchanger for waste heat recovery from exhaust gas of diesel engine. *Procedia Manuf.* **20**, 372–376 (2018)