Waste heat recovery from exhaust of a diesel generator set using organic fluids

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Abstract

Heat available in the exhaust gas of a diesel engine can be an important heat source to provide additional power using separate Rankine Cycle (RC). In this current work, experiments were conducted to measure the available exhaust heat from a 40 kW diesel engine generator set. Performance of an available shell and tube heat exchanger using water as the working fluid was conducted. With the available experimental data, computer simulation was carried out to optimize the design of the heat exchanger. This optimized heat exchanger was then used to estimate additional power considering actual turbine efficiency. Two heat exchangers were used for this purpose. One is used to generate vapour and the other to generate super-heated vapour. Two organic fluids namely Ammonia and HFC-134a were used in this study. The water was also used as working fluid to compare the results. The proposed heat exchanger can produce 10%, 9% and 8% additional power by using water, ammonia and HFC-134a as the working fluids respectively.

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1. Introduction

Compression ignition (CI) engines are a major type of Internal Combustion Engines (ICEs). They are also commonly known as diesel engine. The higher thermal efficiency of these diesel engines has made them popular in applications and they are frequently used for power generation. Trucks, buses and earth moving machineries use high speed diesel engines and output ranges of these engines can vary from 220 kW to 740 kW. Diesel engines are

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also used in small electrical generating units or as standby units for medium capacity power stations. Power generation using ICEs became popular in the last four decades. The main application of these engine derived small power plants were as auxiliary or backup power plants in hospitals, airports, hotels and industry that needed to ensure a reliable power supply at all times. About 10-15% of the total installed capacity in the world is engine based power production nowadays[1, 2].

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 a water-cooled engines about 25% and 40% [3, 4]of the input energy are wasted in the coolant and exhaust gases, respectively. Johnson [5] found that for a typical 3.0 litre 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[3].

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. These technical possibilities are currently under investigation by research institutes and engine manufacturers. Turbocharging[6], cabin air-heating [7], desalination [8] and reducing engine warm-up time [9] are conventional technologies to utilize heat of exhaust gas with a low recovery rate. Relatively new major technologies to recover heat from the exhaust gas include turbo-compounding and bottoming Rankine Cycle (RC). For the heavy duty diesel engines, one of the most promising technical solutions for exhaust gas waste heat utilization appears to be the use of a RC. A RC using water as working fluid is not enough efficient to recover waste heat below 640 K [10]. In this case the Organic Rankine Cycle (ORC) is a promising process to recover the heat from the exhaust of an engine and generate electricity from it [11, 12]. The ORC works like a simple Rankine steam power cycle but uses an organic working fluid instead of water. A certain challenge exists to choose a suitable organic working fluid for the ORC. A question, which also has to be considered for using ORC, is whether an organic substance is really better than water as the workingfluid for a given task.

A systematic approach towards using an installation based on the Rankine Cycle in truck applications dates back to the early 1970s where a research program funded by the US Department of Energy (DOE) was conducted by Mack Trucks and Thermo Electron Corporation [13-15]. Under this program, an ORC system was installed on a Mack Truck diesel engine and the lab test results revealed an improvement of bsfc of 10–12%, which was verified by highway tests. During the following years similar research programs were performed by other research institutes and vehicle manufacturers. Aly[16] was able to produce 16% additional power from the exhaust of a Mercedes-Benz OM422A diesel engine by using R-12 as working fluid for the ORC. ORC systems with capacities from 750 to 1500 kWe were examined by Koebbman[17]. Recently, the solution of Rankine Cycle Systems has increased its potential competitiveness in the market even more [18, 19]. This is a result of technical advancements in a series of critical components for the operation of such an installation (heat exchanger, condenser and expander) but also stems from the highly increased fuel prices. Nowadays, the installation of a Rankine Cycle is not only considered as a feasible solution for efficiency improvement in heavy duty diesel engines for trucks [20, 21] but also for stationary power plant[22].

In this project, experiments were conducted to measure the exhaust heat available from a 40 kW diesel engine generator set at different loads. Two shell and tube heat exchangers were purchased and installed into the engine exhaust system. The performance of the heat exchanger using water as the working fluid was then conducted. With the available data, computer simulation was carried out to improve the design of the heat exchangers. The optimized model of the heat exchanger was then simulated to generate super-heated vapour. Ammonia and HFC-134a were used as the working fluids. Water was used as reference for comparison. For the current study, ammonia and HFC-134a are selected considering some suitable features of these fluids[23]. Finally, power output from the turbine is calculated considering isentropic efficiency of turbine [24].

2. Experimental Setup

The engine used in this study was a 4-stokes, 4 cylinders, water cooled direct injection Hino W04D diesel engine which was coupled with a 50 KVA generator set. The schematic of the experimental setup is shown in Fig. 1. The
A resistive load bank was connected to the generator to put load on the engine. A nozzle was mounted at the air inlet of the engine to measure the air-flow rate. The pressure difference across the nozzle was measured with an accuracy of ±0.01 kPa using an inclined manometer. A digital weighing scale with an accuracy of ±1 g and a stop watch were used to measure the fuel flow rate. From the measured air and fuel mass flow rates, exhaust mass flow rate was calculated. Thermo couples of K type were used to measure the temperatures at different points. The cold and hot fluid side pressures in the heat exchangers were measured with Burdon tube pressure gauges. A variable area flow meter (Make: Dwyer, model: VFA) was used to measure the water flow rate into the heat exchangers. The accuracy of the flow meter was ±5%. A digital tachometer with an accuracy of ±1 rpm was used to measure the engine speed.

The engine was tested at different loads. The exhaust temperatures and air flow rate were recorded to calculate available heat energy from the exhaust. Then the exhaust of the engine was connected to two shell and tube heat exchangers to study the performance of the heat exchangers.

Water mass flow rate, water temperature and pressure were recorded to calculate the effectiveness of the heat exchangers. These data were used to optimize the design of the heat exchanger by computer simulation. The exhaust from the engine was flowed through the tubes of the heat exchangers and the water flowed through the shell side. Counter flow heat exchanger orientation was selected for this study.

3. Heat Exchanger Design Methodology

Two identical shell and tube heat exchangers were purchased from the market. They were then fitted into the exhaust system of the engine and experiments were conducted to estimate the additional power conceivable with this setup. As these heat exchangers were not optimized for this particular application, attempts were made to design heat exchangers that can achieve maximum additional power. Simulation tools were used to simulate the current heat exchangers using experimental data. After acquiring adequate agreement of simulation results with the experimental results, the effects of important parameters of heat exchanger such as length, diameter of the shell, number and diameter of tubes on the performance of the heat exchangers were investigated. The potential additional power was then calculated using actual turbine efficiency [24-26]. As steam expands in turbines, the steam in this application needed to be superheated. Therefore, two heat exchangers were used: one heat exchanger was used to generate vapor from the liquid namely vapor generator and the second heat exchanger was used to generate superheated vapor namely super heater.
4. Modeling Details

As mentioned previously, the purchased heat exchangers were modeled first. Then simulations were carried out to obtain satisfactory results. After achieving satisfactory results, different geometrical aspects of the heat exchanger were optimized. Computer Aided Design (CAD) software, SolidWorks2011, was used to model the existing heat exchanger. The heat exchanger was modelled with 30° triangular staggered array of the tube arrangement. The geometry model was then meshed using ANSYS meshing software. The ANSYS CFX13.0 was used to solve the equations for the fluid flow and heat transfer analysis.

Different meshing schemes were used to make the simulation more accurate. The solid tubes were meshed using sweep mesh whereas the fluid volumes were meshed using tetragonal-hybrid elements. The final refined mesh was selected by comparing the simulation results of model with different mesh density and meshing schemes. The final model has 10,763,968 elements and 4,263,337 nodes and grid independent solution was acquired.

5. Results and Discussion

It is important to know how much energy is available in the exhaust of the engine to design an effective heat exchanger for heat recovery system. In order to find the maximum theoretical obtainable energy from the exhaust, exergy analysis can be utilized. Exergy analysis is a measure for the energy level of the exhaust heat. So some baseline tests are performed. It is found that engine power and the temperature of the exhaust gases have an approximately linear relationship. Exhaust gas temperature increases with increase of power output of the engine. This indicates that heat recovery will be more viable for higher powers. The exhaust gas temperature was found 479 ºC at the engine power of 26.17 kW. Usually an engine is designed to run continuously at this rated power condition. Therefore, this rated power condition was chosen to model the design of the heat exchangers and carry out the simulations. The maximum power of 33.49 kW was not selected because this is in the overload region and usually diesel generator does not operate in this region continuously [27, 28]. It is also found that exergy increases with engine power output. This indicates again that heat recovery is more effective at higher powers. Similar relationship between exergy and engine power was reported in the works of Teng et al. [29]. These results indicate that approximately 50% of the engine’s power is currently wasted but could be recoverable and converted to usable form.

The effectiveness of the existing heat exchanger, found from the experimental results and CFD simulations are presented in Fig. 2. It is observed that the effectiveness predicted by CFD simulation is approximately 10% higher than the experimental values for all power ranges. During the experiment, there were some sources of fouling in both the hot and cold fluid sides. The exhaust contained soot and particles which increased resistance for the heat transfer inside the tubes and the water used in the experiment lacked treatment, consequently there was fouling effect on the shell side. These effects were not considered in the CFD simulation and causes the over prediction of effectiveness than the experimental results.

Based on the available data from the experiment, the heat exchanger design was optimized by computer simulation. Fig. 3 shows that the effectiveness of the heat exchanger increases with the increase of number of tubes for all three working fluids. It is evident that as the number of tubes increases, the effectiveness also increases due to
the increase of the surface area of tubes and the effective velocity inside the shell. The highest effectiveness was found to be 0.77 for 31 tubes and this number of tube was selected for the next study. The next parameter of the heat exchanger investigated was the length and the results are presented in Fig. 4. The maximum effectiveness was found 0.80 for 2 m length of the heat exchanger and this length was selected for the proposed heat exchanger. In the previous work it was shown that the effectiveness of the heat exchanger decreases with increasing shell diameter [6, 22, 30]. After optimization, the final proposed heat exchanger had a shell diameter of 90 mm, 31 tubes, 50% cut 7 baffles, and an effective length of 2 m.

Additional power that could be recovered from the exhaust of the diesel engine with the proposed shell and tube heat exchangers is presented in Fig. 5. The additional power generation was calculated at different working pressures for the three working fluids. It is found that additional output power increases as the working pressure increases for all three working fluids. This is because the condensing pressure was kept constant and as the working pressure increases the enthalpy drop across the turbine also increases. From the figure it is clear that water can recover heat most efficiently from the exhaust of the engine than the other organic fluids. This is because water has very high enthalpy drop across the turbine compared to other two organic fluids. The proposed shell and tube heat exchanger can recover maximum 10%, 9% and 8% additional power from the exhaust of the diesel engine using water, ammonia and HFC-134a as working fluid respectively considering 80% isentropic efficiency of the turbine [24, 25].

6. Conclusion

The exhaust of a diesel engine contains 40% of the input energy and usually this energy is wasted by expelling to the environment. The overall efficiency of the diesel engine can be improved by recovering this waste heat to produce additional power by turbine using ORC. In this project, experiment was conducted to estimate available energy in the exhaust gas of a diesel engine and the experimental data was used to improve the design of the existing shell and tube heat exchanger by computer simulation. Water, ammonia and HFC-134a are used as working fluids. The effectiveness of the optimized heat exchanger is found to be 0.78. Additional 10%, 9% and 8% more power can be achieved with the proposed shell and tube heat exchanger by using water, ammonia and HFC-134a respectively.

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