Improvement on Performance of a Heavy-Duty Diesel Truck Engine by Utilizing Waste Heat Energy with Organic Rankine Cycle

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Abstract

Automotive sector is highly competitive and looking solution for performance improvement as well as emission reduction as per regulation. When analysing heat balance of IC engine, about 50-55% of heat energy is wasted, particularly at cooling and exhaust systems. It is possible to recover some amount of waste heat with additional power generation system. ORC is one such method which has high potential in heavy duty diesel engines. A Volvo D13K540 engine is selected for this analysis. The maximum power output of the engine is 397 kW at the speed range of 1450 rpm to 1800 rpm. 1-D engine simulations are carried out with Ricardo Wave software to estimate heat load. In the present study, waste heat recovery from engine exhaust gas alone is considered. Engine simulations at various operating conditions are performed to estimate the available heat energy in order to develop ORC system. About 28% of energy supplied to the engine is rejected in the exhaust gases. Equipments associated with the ORC cycle is modelled with DWSim software for simulations. It has been observed that the combined power of the system is increased to 425 kW. It is equivalent to improvement in BSFC by 6.3%

Keywords: Organic Rankine Cycle, Specific Fuel Consumption, Waste Heat Recovery, Automotive Diesel Engine

NOMENCLATURE

\[ C_p \] Specific heat at constant pressure (kJ/kg-K)
\[ h \] Enthalpy (kJ/kg)
\[ m \] Mass flow rate (kg/s)
\[ Q \] Heat flow rate (kW)
\[ T \] Temperature (K)
\[ W \] Power (kW)

Subscript

1,2,3,4 State points A,B,C,D respectively
\[ a \] Ambient temperature
\[ c \] Condenser
\[ e \] Expander
\[ evp \] Evaporator
\[ ex \] Exhaust
\[ p \] Pump
\[ w \] Working fluid

Acronyms

ORC Organic Rankine Cycle
BSFC Brake Specific Fuel Consumption

1. INTRODUCTION

In past two decades, automotive industries underwent tremendous changes for improving engine efficiency and emission reduction. These improvements are as a result of implementation of various technologies like variable valve timings, exhaust gas recirculation, improvement in fuel injection system and combustion process etc. In most of the cases, developments are focused on making modifications to the flow thermal process of engine itself. In the present study, importance is given for improving the efficiency of vehicle, outside engine level. For example, in the case of heavy-duty diesel engine, almost 50-55% of the energy is lost as heat energy in engine exhaust and cooling system. Though turbochargers are used to extract some energy from exhaust gases, it is also possible to generate power from low quantity remaining heat available from exhaust with the help of Organic Rankine Cycle (ORC). The ORC is used in stationary engine applications is shown in Fig 1. Currently, experiments with ORC are carried out for heavy duty diesel engine [1].

ORC is similar to Rankine cycle used in thermal power plant with water as working fluid. The main difference arises in the properties of fluid. Water is normally used as the working fluid in Rankine cycle. It is a wet fluid and has a negative slope in the T-S diagram. Hence, when the expansion process takes place it passes through two-phase zone and requires superheating for improving efficiency. On the other hand, dry fluid has positive slope. The fluid like R11 is referred as isentropic where the entropy is constant along liquid vapor interface. In ORC, one can use either dry or isentropic fluids. ORC is used when the temperature of the heat source is below 640 K [2].

The thermodynamic processes in the ORC are shown in Fig. 2. A is the initial state point. During A to B, the
The main aim of the study is to evaluate the improvement in Break Specific Fuel Consumption (BSFC), while utilizing power generated from ORC to generate power from waste heat energy in engine exhaust. As the emission standards are getting stringent, possibilities of improving the efficiency of vehicle from engine level and outside engine has to be considered.

### 2. METHODS AND METHODOLOGY

The methodology consists of two parts. In the first part engine simulations are performed with the help of Ricardo Wave software to obtain heat flow rate in engine exhaust gas. Using this data, in the second part, ORC simulations are performed with the help of DWSim software to obtain the additional power output. The details of both the simulations are discussed below.

#### 2.1 Engine Simulation

The 1-D engine simulation is carried out in Ricardo Wave software. The engine selected for the simulation is Volvo D13K540. It is a 12.8-L 6-cyl engine. The engine specifications have been provided in Table 1.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine CI</td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>12.8 L</td>
</tr>
<tr>
<td>No. of cylinder</td>
<td>6</td>
</tr>
<tr>
<td>Bore</td>
<td>131 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>158 mm</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>17:1</td>
</tr>
<tr>
<td>Max. Power</td>
<td>397 kW @1400-1800 rpm</td>
</tr>
<tr>
<td>Max. Torque</td>
<td>2600 Nm @1050-1400 rpm</td>
</tr>
</tbody>
</table>

Based on the above specification a Ricardo Wave engine model is created. Various sensors for measuring mass flow rate and temperature are placed in exhaust duct. It is shown in Fig.3. Simulations have been conducted for various engine load conditions. The data obtained from simulation is exported to Matlab for post processing with contour plots.

The BSFC and power output of engine for complete operating conditions are plotted and is shown in Fig. 4 and 5 respectively. It can be seen that engine has a most efficient BSFC of 0.1925 kg/kW·h. The rated power of the engine is 397 kW.

For designing the ORC system, the waste heat flow rate in engine exhaust has to be evaluated. The mass flow rate and temperature of the exhaust gases are obtained after engine simulation. Based on these simulated values, the heat flow rate in engine exhaust can be calculated with help of the following formula.

\[
Q_{ex} = m_{ex} \cdot C_{p(ex)} \cdot \Delta T
\]
Where
\( Q_{ex} \) is the heat flow rate in exhaust.
\( m_{ex} \) is the mass flow rate of exhaust gas.
\( C_P(ex) \) is the specific heat of engine exhaust at constant pressure.
\( \Delta T = T_{ex} - T_a \)
\( T_{ex} \) is the exhaust temperature measured with the help of sensors.
\( T_a \) is ambient temperature.

The specific heat of engine exhaust gas can be calculated with the help of formula
\[
C_P(ex) = 0.00025 T_{ex} + 0.99
\]
Fig. 6 shows heat flow rate in engine exhaust system. As expected, the waste heat energy rate in exhaust gas is almost equal to useful power developed by the engine. The maximum heat flow rate in engine exhaust is 280 kW which occurs at peak rpm at full load condition.

Based on the literature review R245fa is selected as the working fluid [1,3,4]. The mass flow rate of R245fa is selected based on the heat flow rate in engine exhaust. While selecting the mass flow rate of the working fluid, focus has to be given such that the working fluid would not pass through two phase regions inside the expander. Otherwise, it can result in expander erosion [5, 6]. This will also result in reduction of the performance of the ORC System.

Engine simulation at 75 points provided various values for exhaust heat. The refrigerant mass flow rate is to be adjusted in such a way that it will not undergo two phase regions. This was performed with trial and error method in DWSim. The flow rate of working fluid for various operating conditions is shown in Fig. 7. The maximum flow rate of R245fa required for the ORC system is 1 kg/s. In actual practice, the mass flow rate of R245fa should be regulated with help of a control system, based on the engine operating conditions.

In order to quantify the performance benefit, the power output from the expander is added to the engine power output. Hence,
\[
\dot{W}_{power_{combined}} = \dot{W}_{eng} + \dot{W}_{arc}
\]

3. RESULTS AND DISCUSSION

3.1 Comparison of power output

The combined power of ORC system can be seen in Fig. 8. It is observed that the power output of vehicle has improved from 397 kW to 425 kW utilizing waste heat recovered from engine exhaust gas with organic Rankine cycle. Similar values are reported with experiments [1].
3.2 Comparison of BSFC

The equivalent BSFC is calculated with improved power output without change in fuel consumption. Since the power output is increased, the BSFC will decrease. The BSFC of the combined system is shown in Fig. 9. The engine has a lowest BSFC of 0.1925 kg/kW·h, as shown in Fig. 4. The lowest BSFC of the vehicle has been improved to 0.181 kg/kW·h with help of waste heat recovery from exhaust system. As expected, the fuel economy region is not changed.

The percentage of improvement in BSFC from vehicle with and without ORC system is calculated and plotted and shown in Fig. 10. There is an improvement of BSFC by 6.3 % for ORC system in the fuel economy regions.

4. CONCLUSION

Thermodynamic analysis study is carried out on an automotive diesel engine to obtain an estimate for performance improvement by utilizing waste heat energy from exhaust gases with the help of ORC plant. Volvo D13K540 engine is modeled in 1-D Ricardo Wave software and simulations are performed for 75 operating conditions. The engine characteristic curves are plotted, and the following observations are made.

- The engine has lowest BSFC of 0.1925 kg/kW·h when it operates in the range of 1400-1500 rpm and has a BMEP of 14-18 bar.
- The maximum heat flow rate in exhaust is 280 kW at 2100 rpm.

Various components of ORC system are properly modelled and R245fa is considered as working fluid. Special attention is given for pressure drop in the heat exchanger and mass flow rate of working fluid. The ORC simulations are performed with the help of DWSim open-source software. The following observations are noticed while using exhaust gas heat is considered as source for evaporator in ORC.

- The maximum power output from expander is about 27 kW.
- By considering power improvement from the expander, the equivalent BSFC for system has a value of 0.181 kg/kW·h
- The estimated average improvement in BSFC is about 6.3 %.

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