
Jingye YANG*, Binbin YU*, Bingqing LU*, Jiangping CHEN†

*Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University
(No. 800, Dong Chuan Road, Shanghai 200240, PR China)

Summary
Heavy-duty diesel engines have been widely applied in commercial vehicles. However, escalating consumption of fossil fuels and stringent legislation of CO₂ emission have raised the concern about searching for viable technologies to improve the fuel energy efficiency recently. Generally, optimization technology of engines can be categorized into two types: engine-powertrain-applied and engine-bottoming cycles. The bottoming organic Rankine cycle is an applicable combined heat and power (CHP) technology with great potential for engine waste heat recovery. The aim is to increase the fuel energy efficiency without additional fuel consumption. In this paper, a thermo-economic overview of organic Rankine cycle system integrated into engines especially for on-the-road vehicle is presented. First of all, characteristics of various engine waste heat (e.g. exhaust gas, EGR, CAC, jacket cooling water, oil circuit) are briefly analyzed; Afterwards, special attention is paid to the screening criteria of appropriate expansion machine and working fluid selection; Subsequently, an overview of various layout of organic Rankine cycle was presented; Eventually, cost-orient economic evaluation of the synthesis cycle is overviewed, which is meant for characterizing the optimum system design.

Keywords: Review, Organic Rankine Cycle, Engine, Waste heat recovery

1. Introduction
Heavy-duty diesel engine and Internal combustion engine are both primary dynamic sources of on-the-road vehicles. However, almost 60%-70% of fuel energy is wasted through engine exhaust gases. Increasing price level of fossil fuel and more stringent legislation of green-house gas emission promote the evolution of energy conversion technologies. In 2010 US EPA report, fossil fuel use and industrial process are the primary source of carbon dioxide (CO₂) account for 65% of GHG (Green House Gas) emissions. Petroleum-based fuels, gasoline and diesel are the main transportation energy. 14% of global green-house gas emissions come from transportation involved with fossil fuel burned for road, rail, air, and marine transportation. In July 2009, European Union leaders and the G8 announced that green-house gas emissions should be reduced at least 80% below 1990 levels by 2050. This resulted in a practical guide to a low-carbon Europe called Roadmap 2050. A conversion of fossil fuel to electricity in transportation is suggested as one of the modifications of energy systems. Engine manufactures can be categorized into two types: one is the engine-powertrain-applied technologies. Coupling engines with EGR (Exhaust Gas Recirculation) for NOx reduction, variable valve timing, engine downsizing, enhanced fuel mixing and turbocharging are main strategies; Another one is bottoming technology, advanced after-treatment and waste heat recovery are both engine-tailpipe strategies. Waste heat recovery is assumed as a promising technology to improve the energy efficiency and decrease emissions effectively without additional fuel consumption. Overviews of Thermo-Electric Generators (TEG) were reported in Hamid Elsheikh's and Orr B's researches. Aghaali H presented a literature review of turbo-compounding technology as waste heat recovery from ICE (Internal Combustion Engine). Organic Rankine cycle offers an interest in better use of fossil fuel through conversion from engine waste heat to electricity, which is known as combined heat and power generation technology. Anh Tuan Hoang conducted an overview of the latest technology of organic Rankine cycle for engine waste heat recovery application. Different temperatures of waste heat especially the diesel engines were concentrated on. Mahmoudi et al. presented an overview of last four years research works on ORC application. Cycle configurations, working fluid selection and operating conditions were included in the investigation. The thermo-economic overview of organic Rankine cycle implemented in this paper is concentrated on vehicle engines. The remainder of this review is processed with four main sections. First section is the investigation of vehicle engine background including heat source characteristics of engine waste heat. Second section presents a detailed review of organic Rankine cycle technology including selection of working fluid and expansion machines. In the third section, a summarize of various layout of ORC system was discussed; The last section is the summary of cost-orient economic evaluation criteria of organic Rankine cycle system.

2. Characteristics of Engine Waste Heat Recovery
Engine waste heat can be divided into two categories according to temperature level: medium-high temperature heat source (e.g. Exhaust Gas (200-600 °C), Exhaust Gas Recirculation (200 °C - 750 °C)); medium-low temperature heat source (e.g. Coolant (80 °C -100 °C), Lube Oil (80 °C -120 °C),...
Charge Air Cooling (50 °C -70 °C)). Internal combustion engine exhaust gas temperature varies from 500 °C -900 °C which is dependent on different engine types and variable operating conditions. Although exhaust gas contains large amounts of waste heat, extremely high temperature brings difficulties in waste heat recovery procedure. First is the thermal match between heat source and high temperature working fluid. Organic working fluid is not suggested here because of decomposition. Usually, an additional heat oil heat exchanger is introduced to cool the exhaust gas to a normal temperature around 200 °C. In that case, thermal stream is more stable while considerable heat is lost as price. Second is the sealing design of heat exchanger. High quality design of evaporator is demanded to avoid leakage and corrosion.

Simon et al.15) has reviewed the thermal power of exhaust gas and EGR of four different heavy-duty diesel engines in Figure 1. They are single-stage turbocharged engine with no EGR, a single stage turbocharged engine with high pressure (HP) EGR, a two-stage turbocharged engine with HP EGR and another two-stage turbocharged engine with HP EGR. EGR is presented as an effective aftertreatment technology with high energy potential, which is assumed as the most attractive heat source. Previous researches revealed that heat source temperature under 80 °C has little value to recover. Although there is an ‘apparent’ amount of heat in coolant, system thermal efficiency can be quite low. Chammas et al.16) reported that the exhaust gas carries waste energy ranging from 4.6 to 120 kW while cooling water carries heat ranging from 9 to 48 kW for a typical light duty 4-cylinder spark ignition engine. Organic Rankine cycle is proposed as a viable bottoming technology for engine waste heat recovery. Thermal match between two systems decides the overall coupling cycle efficiency. Off-design operating conditions bring time-varying heat source temperature and mass flow rate which is hard to predict. Thus, data about variable heat source is necessary for ORC performance evaluation. They are usually reported with engine load or speed steady-state points both experimental and simulative. Torque-speed map is also counted for describing the driving cycle. Domingues et al.17) has investigated six different working points of one typical engine. Vehicle speed, engine power, heat source temperature and mass flow rate are analyzed as seen in Table 1.

3. Screening Criteria of Scroll Expander and Working Fluid Selection

Working fluid selection is dependent on characteristics of heat source and operating conditions. Classification of working fluids is diversified in different aspects. In the previous literatures, working fluids are usually defined with the vapor status at the end of expansion process. Most wet fluids are inorganic like water and ammonia. The slope of saturation vapor curve is negative in T-S diagram. Exhaust vapor at the outlet of the expander may exceed the two-phase region, which will damage turbo type expanders. The slope of saturation dry fluid vapor curve is positive while vertical for isentropic fluids. Existence of superheating is assumed

![Fig. 1 Exhaust gas and EGR thermal power for four different HDDE models at full load condition](image)

<table>
<thead>
<tr>
<th>Operating point</th>
<th>Vehicle speed (km/h)</th>
<th>Engine Power (kW)</th>
<th>Exhaust gas mass flow rate (g/s)</th>
<th>Exhaust gas temperature (°C)</th>
<th>Recoverable exhaust heat (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>12.8</td>
<td>457.8</td>
<td>5.0</td>
</tr>
<tr>
<td>2</td>
<td>23.5</td>
<td>13.0</td>
<td>25.9</td>
<td>595.1</td>
<td>14.3</td>
</tr>
<tr>
<td>3</td>
<td>47.2</td>
<td>26.4</td>
<td>43.0</td>
<td>716.7</td>
<td>18.4</td>
</tr>
<tr>
<td>4</td>
<td>67</td>
<td>37.2</td>
<td>59.7</td>
<td>792.2</td>
<td>46.1</td>
</tr>
<tr>
<td>5</td>
<td>80</td>
<td>44.1</td>
<td>71.9</td>
<td>800.7</td>
<td>57.2</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>54.4</td>
<td>92.4</td>
<td>804.1</td>
<td>73.9</td>
</tr>
</tbody>
</table>
unnecessary to dry fluids since over superheated vapor of expander will increase the cooling load of condenser, thus an additional recuperator is suggested to improve the system thermal efficiency. In accordance to the origin source, working fluids can be categorized into nature fluids (e.g. water, carbon dioxide, ammonia) and organic fluids (e.g. alcohol, refrigerants). Based on the heat source temperature, working fluids can be classified into medium-high temperature working fluids (e.g. alcohol, steam water, hydrocarbon) and medium-low temperature working fluids (e.g. R245fa, R134a, R1234yf). Pure fluids can hardly satisfy the thermal match between working fluids and heat sources since various waste heat exist in vehicle engines. Mixtures including water soluble matter and zeotropic fluids are proposed to bring the temperature glide to better match the heat source and decrease the exergy loss.

However, the downside of zeotropic fluids is the insufficient phase change that weakens the heat transfer process. Screening criteria of working fluid selection is important since appropriate working fluid is beneficial to improve cycle performance. Thermophysical properties of working fluids, global safety criteria and environmental impact are main considerations. Thermophysical properties are referred to the critical temperature/pressure of working fluids, saturation slope after expansion (ds/dT), condensation pressure and molecular weight. Environmental impact indicators include GWP (Global Warming Potential) and ODP (Ozone Depletion Potential). Global safety criteria are concerned with flammability, toxicity and corrosivity. Actually, considering the significant impact of HFCs to climate change, several investigations have been focused on the refrigerant substitute procedure. In 2014, Datla and Brasz\textsuperscript{28} first-time carried on an experimental study with a 75-kW basic ORC using radial inflow turbine. They revealed that R1233zd(E) led to 8.7% higher net cycle efficiency and more output electricity than R245fa. Matthias Welzl et al.\textsuperscript{19} proposed a comprehensive evaluation of organic Rankine cycle combining nucleate boiling heat transfer coefficient (HTC) with output electricity. The higher HTC and better performance of R245fa than R1233zd(E) at the same saturation temperature can be explained by the higher pressure and density. Sebastian Eyner et al.\textsuperscript{20} reported that R1233zd(E) performed approximately 7% higher thermal efficiency but with 12% lower gross power output.

Scroll expander is chosen as an appropriate expansion machine for small-scale organic Rankine cycle because of fewer moving parts, reliability, lower noise and vibration\textsuperscript{21}. Usually, the categorization of scroll expander is dependent on the operation way: one is velocity expansion machine, another is volumetric machine. However, in this paper, two types of scroll expander are characterized by the manufacture: One is design expander, another is the modified expander from commercial compressor. George et al.\textsuperscript{22} designed an open-drive scroll expander and integrated it into ORC system. Theoretically, the specifically designed expander is more adapted to the operating pressure ratio. However, the isentropic efficiency is only 25-40%, which is lower than expected. The main reason is the limited expander rotational speed (500 rpm) that leads to large internal leakage and decrease the expansion performance. The modified scroll expander is widely utilized in experimental investigation. Woodland et al.\textsuperscript{23} experimentally investigated an open-drive scroll expander integrated into a micro-scale ORC system. The peak of expander isentropic efficiency occurs when the filling factor is near a unity and the expansion volume ratio is near the built-in volume ratio. The deviation between the expansion volume ratio and the designed value results in drastic decrease in expansion performance. This explains why the specifically designed expansion machine is more efficient than the modified one, theoretically. The optimization of scroll expander based on a simulative model is relevant to improve the system performance. Usually, there are two ways of modeling: thermodynamic modeling and mathematical modeling. For thermodynamic modeling, there is no need to know the exact geometry of expansion machine. Operating conditions are paid more attention to. Lemort et al.\textsuperscript{24} had proposed a simplified thermodynamic modeling method of open-drive scroll expander. Pressure-drop and internal leakage are both modelled with an isentropic fluid flow through a nozzle. The heat transfer procedure is modelled as a heat exchanger. Filling factor and expander isentropic efficiency are used to fully characterize the expansion performance. Yanagisawa\textsuperscript{25} experimentally tested a modified scroll expander in 1988. The expansion adiabatic efficiency can be reached between 60%-75% for the speed range of 1000 - 4000 rpm.

Mathematic modeling of expander is much more complicated since bunch of geometric parameters are demanded. Large amount of experimental data is demanded to validate the mathematical model. Although the modeling procedure is more complicated, the geometric optimization can be realized based on such simulative model.

4. Layout of Organic Rankine Cycle System

Apart from the single-pressure organic Rankine cycle system, there are also different layouts of ORC developed by researchers, which is aimed to improve the cycle thermal efficiency. Several literatures have been concentrated on the various configurations of organic Rankine cycle systems. Kevin Rosset et al.\textsuperscript{26} theoretically evaluate the various cycle configurations and working fluids of ORC system for passenger car internal combustion engine application. The available space in the engine and the condenser were considered as the most important factors that influence the system performance. Xuan wang et al.\textsuperscript{27} Compared four forms of organic Rankine cycle with the dynamic math model on the SIMULINK. The aim is to reveal the effect factors of part-load performance. In this section, four different types of organic Rankine cycle were introduced, as shown in Figure 2. Upper left is the basic ORC with only four main components. The whole system is simple, compact but the cycle thermal efficiency may be unsatisfying considering large heat load was waste in condenser side. The upper right is a basic ORC with an additional preheater. The waste heat in radiator and coolant were recovered to preheat the coming cold refrigerant. The low-grade waste heat can be taken advantage using this method. The down left is a regenerate ORC system. The regenerator takes advantage of the
resume heat of the exhaust vapor at the end of the expansion to preheat the cold fluid flow before evaporator. The last one is a conceptual schematic of dual loop ORC with two expanders and pumps. It was considered as the most complicated configuration since the number of each component was doubled than the basic ORC. In that case, the experimental cost will be increased. Based on the previous literature review, an opinion is drawn as: considering the trade-off between the component cost and the improvement in effectiveness, the basic ORC was assumed more appropriate since the available room in vehicles is limited. Moreover, the integral weight of the system should be controlled in a smaller value.

![Basic ORC](image)

![BORC with preheater](image)

![Regenerate ORC](image)

![Dual-loop ORC](image)

Fig.2 Layouts of organic Rankine cycle

5. Cost-orient Economic Evaluation

There are plenty of economic analysis of ORC system in previous literatures. In this paper, a summary of several cost-orient evaluation indicators is presented. Before implementing the evaluation criteria, an economic modeling is demanded. APR, SIC and LCOE are the most commonly used indicators. APR is defined as the ratio of heat exchanger area to net power output; SIC is referred to the specific investment cost; LCOE is the levelized cost of electricity. Lecompte et al.\(^\text{29}\) proposed SIC\(^\text{pl}\) for part load consideration of the system. It’s defined as the ratio of investment cost to annual average net power output. Such indicator not only takes the heat transfer procedure into account but also the ambient conditions. Economic evaluation methods presented above are all related to the systematic performance. Expander size factor (SF) is used to quantify the cost of expansion machine. It is defined as a ratio between exhaust specific volume and heat transfer rate in evaporator. Minimizing the SF value is one of the optimization objectives of expander. The total heat transfer capacity is specific for economic evaluation of heat exchangers, which is related to the geometric design of heat exchangers and working fluid selection.

6. Conclusion

Engine waste heat is presented as an appropriate heat source to recovery. Large amount of energy is contained in exhaust gas and EGR. Organic Rankine cycle is supposed to be used for low-grade waste heat recovery with great potential. Screening criteria of working fluid selection and expansion machine selection are paid attention to in previous researches. Thermo-physical properties, environmental impact and safety concern are three main considerations for working fluid selection. Modified scroll expander is proved applicable in ORC system with potential. Considering the trade-off between the experimental cost and the cycle thermal efficiency, the single-pressure basic ORC was considered the most appropriate for engine waste heat recovery. Cost-orient economic evaluation is important as well for further consideration of commercial production in the future.

References

2) https://www.epa.gov/climate%20change/ghg%20emiss

5) Codan E, Vlaskos I ABB turbocharging – turbocharging medium speed diesel engines with extreme Miller; n.d.


