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Alkanes based two-stage expansion with interheating Organic Rankine cycle for multi-waste heat recovery of truck diesel engine

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ABSTRACT

The environment issue combined with the rising of crude oil price has attracted more attention in waste heat recovery of diesel engine. The Organic Rankine cycle (ORC) offers a good solution to utilize multi-grade waste heats of diesel engine. Conventional multi-source ORC systems are too complex for vehicle application. This paper proposed a two-stage expansion with interheating organic Rankine cycle (ORC) system using alkanes as working fluids, in order to recover multi-waste heats (exhaust gas, EGR gas and engine coolant) with simple system configuration and solve the problem of overlarge expansion ratio of alkanes. Thermodynamic models based on first and second thermodynamic law are established. A correlation was proposed to estimate the optimum intermediate pressure to achieve maximum net power output. System performance comparison among alkanes shows that cyclic alkanes are superior to linear alkanes regarding net power output, thermal efficiency and exergy losses although they are weaker in recovering heat from engine coolant. Compared with the conventional preheating-regenerative ORC system, the proposed system can recover waste heat of exhaust gas (100%) and EGR gas (71.8%) more efficiently and generate 6.7% more output power, and it is more compact in terms of heat exchangers size, pump volumes and turbine structure.

1. Introduction

The China Ministry of Transport reports that the truck freight transportation, mostly powered by the heavy-duty diesel engine, has consumed about 49.2% of total transportation fuel consumption. In US, truck freight transportation accounts for 70.1% of domestic freight volume and contributes to 25% of domestic greenhouse gas emissions and fuel consumption [1]. Escalating crude oil price and environmental problem are attracting more attention in methods to further improve the thermal efficiency and reduce emissions of truck diesel engine. For the conventional truck diesel engine, only 30–45% of fuel combustion energy can be converted into effective power output while more than half of fuel energy is still rejected to environment via the exhaust gas, exhaust gas recirculation, engine coolant and charge air [2]. Several technologies have been researched to recover waste heat from truck diesel engine since there is considerably heat recovery potential for truck diesel engine. Among all the waste heat recovery technologies, Organic Rankine cycle has got more attention for its high efficiency with suitable size for trucks, low impact on the engine backpressure [3,4] and capability of recovering various waste heats from diesel engine [5].

Extensive previous researches have been done on the ORC-based waste heat recovery systems which only absorb heat from exhaust gas of diesel engine [6–9]. However, there is considerable heat recovery potential in other forms waste heat of diesel engine. To further improve engine efficiency to meet stricter emission regulation, various waste heat sources of engine should be exploited. However, the diversity and multi-grade characteristic of engine's waste heat sources makes it difficult to be utilized efficiently [10].

For single-loop system, preheating ORC system is widely studied to recover both exhaust gas and engine coolant. Chammas and Clodic [11] built a preheating ORC system powered by exhaust gas and engine coolant of an electric hybrid vehicles. Up to 32% fuel economy improvement can be achieved. Vaja and Gambarotta [12] compared three different cycles setups including simple cycle, preheating cycle and regenerative cycle and revealed that preheating cycle was possible to enhance engine efficiency by 12.5%. Yu et al. [13] studied the preheating ORC system and showed

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thermal efficiency of diesel engine can be improved up to 6.1%. Kim et al. [14] proposed a single-loop preheating ORC system with regenerators and it produces approximately 20% additional power. However, conventional single-loop ORC system is incapable of recovering other waste heat sources due to restriction of cycle configuration.

To take full advantage of multi-source waste heat energy of diesel engine, the cascade-Organic Rankine cycle (C-ORC) has been investigated in previous papers. Shu et al. [10,15] proposed a C-ORC system to recover waste heat from an truck diesel engine's exhaust gas, exhaust gas recirculation, engine coolant and charge air. Tao et al. [5] presented a novel confluent cascade expansion ORC system to recovering waste heat from exhaust gas and engine coolant efficiently. Dolz et al. [16] studied different bottoming Rankine cycles with water-steam and/or ORC configurations for a heavy-duty diesel engine to recover all waste heat sources (including exhaust gas, exhaust gas recirculation, engine coolant and charge air). Zhang et al. [17] presented a novel dual-loop bottoming organic Rankine cycle with a light-duty diesel engine to recover waste heat from exhaust gas, intake air and engine coolant. As summarized above, the C-ORC is capable of recovering multi-source waste heat energy of diesel engine. However, the C-ORC systems are too complex, bulky and heavy to truck diesel engine [5,14]. Further studies are still required to explore simple configuration to utilize multi-waste heats of diesel engine effectively.

The working fluid choice is another main issue when developing Organic Rankine cycle system to recover waste heat from truck diesel engine. Considering the high-temperature characteristic of waste heat from vehicle, many refrigerants can be excluded as solution. Among working fluids, alkanes-based working fluid have been employed by ORC manufactures in order to achieve better performance in some high-temperature applications since higher working fluids temperature can be reached by alkanes [7,18,19]. Lion et al. [20] reviewed the ORCs for vehicle heavy duty diesel engine applications and indicated that hydrocarbons (HCs) commonly showed good performance for medium-high temperature waste heat recovery from diesel engine. Tian et al. [21] compared siloxanes and alkanes in a regenerative transcritical dual-loop organic Rankine cycle which recover waste heat of exhaust gas and engine coolant from a diesel engine, results showed that alkanes are 5.8–8.6% higher than siloxanes in terms of thermal efficiency. Siddiqi and Atakan [19] compared alkanes with water and revealed that alkanes are suitable fluid in exhaust temperature range of diesel engine. Shu et al. [7] studied alkanes-based ORCs system to recover exhaust gas waste heat and concluded that alkanes are attractive for diesel engine waste heat recovery. However, there are still some problems to prevent alkanes from vehicle application use, one of which is that overlarge expansion ratio makes it difficult to select and design proper expander [7,22].

In order to solve the above-mentioned problems, this paper proposed a two-stage expansion with interheating organic Rankine cycle system using alkanes as working fluids. This system can exploit multi-source waste heat (including EGR gas, exhaust gas and engine coolant) of truck diesel engine with simple cycle configuration. Meanwhile, expansion ratio of turbines in this system can be kept in reasonable range due to two-stage expansion. In this paper, thermodynamic models based on first and second thermodynamic law are established firstly. The effect of intermediate pressure on system performance is investigated and the optimum intermediate pressure is determined. And then, the system performance comparison among different alkanes is conducted from their properties. Finally, the proposed system is compared with the preheating regenerative ORC system in terms of system performance and component size.

2. System description

2.1. HD diesel engine description

The studied truck heavy duty diesel engine in this paper is an 8.42 L turbocharged and intercooled diesel engine with exhaust gas recirculation (EGR), and the main parameters are listed in Table 1. The rated power is 243 kW at 2200 rpm, while the maximum engine torque is about 1333 N m around 1700 rpm. Normally, the waste heat recovery system should be designed based on the working conditions at which the HD diesel engine operate for most of the time. According to ref. [5,23], for the heavy duty truck running in urban areas, the frequent engine's working points are located in the region with the middle speed and 50–100% engine load. Therefore, the working point of maximum engine torque at 1700 rpm is chosen as the design point of waste heat recovery system. The detailed heat source parameters are shown in Table 2. If the heat transfer capacity of heat exchangers and flow capacity of turbine are capable under design condition, it is confirmed that system can operate well in engine's frequent working areas.

2.2. Description of system

The structure of the two-stage expansion with interheating organic Rankine Cycle system is shown in Fig. 1. The engine coolant, exhaust gas and EGR gas are used as the heat source of preheater, evaporator and reheater respectively. Due to relatively high critical temperature and safety concerns, subcritical cycle is applied in this paper. First of all, the saturated working fluid is pressurized through pump to the set evaporating pressure (1–2). The working fluid at the pump outlet is heated by engine coolant in preheater (2–3) and then heated by exhaust gas in evaporator (3–4) to maximum turbine inlet temperature. Superheated vapor is only expanded to an intermediate pressure in the turbine 1 (4–5). Next, working fluid is reheated back to maximum turbine inlet temperature by EGR gas in reheater (5–6) and expanded through the turbine 2 to the condensing pressure (6–7). After leaving the turbine 2, the exhausted working fluid vapor enters the condenser, in which saturated liquid is generated after condensation process and then a cycle complete.

Compared with conventional dual-loop ORC system, the proposed system is compact enough for multi-waste heat source recovery from truck diesel engine. Only one kind of working fluid and one pump are needed in this system. Hence, the total weight and volume of the proposed system can be smaller than conventional dual-loop ORC system.

3. Alkane

Alkanes are kind of simple chemical compounds only composed by hydrogen and carbon atoms. In an alkane, each carbon atom has

Table 1
Main parameters of the studied heavy-duty diesel engine.

Parameters	Value/descriptions
Engine type	In-line, six cylinders
Cylinder diameter × stroke length (mm × mm)	113 × 140
Total displacement (L)	8.42
Compression ratio	16.8
Swirl ratio	1.25
Combustion chamber	Reentrant type
Fuel inject system	Bosch common rail
Air intake mode (–)	Supercharged intercooled
Rated power (kW)/rated speed (rpm)	243/2200
Maximum engine torque (N·m)	1333 (at 1700 rpm)