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Evaluation of a small-scale waste heat recovery organic Rankine cycle

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HIGHLIGHTS

- Utilization of exhaust gas heat by means of small-scale ORC was studied.
- High molecular weight siloxane MDM was used as the working fluid.
- Experimental study was carried out at different operational conditions.
- The potential for designing small-scale ORC systems with high efficiency was confirmed.

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ABSTRACT

In recent years, the use of small-scale organic Rankine cycles (ORC) in exhaust gas heat recovery of reciprocating engines has been intensively studied. In this paper, the working fluid selection and experimental results of a small-scale ORC unit utilizing exhaust heat of a diesel engine are presented and discussed. Based on the working fluid selection study, siloxane MDM was evaluated as the most suitable fluid for the experimental system. The experiments were conducted with the aim of studying and analyzing the capability of the ORC process of recovering heat from the diesel engine exhaust. The high pressure MDM vapor was expanded through an expansion valve; thus, no power was extracted from the experimental setup and the main focus was on studying the performance of the process heat exchangers. The system under study was identified to be capable of efficiently recovering the waste heat of the exhaust gases, and the potential of using high molecular weight and high critical temperature fluids as the working fluids in high-temperature, small-scale ORC applications was confirmed. It was concluded that when using siloxane MDM as the working fluid, the requirements for the process sealing to withstand low vacuum conditions as well as the effective removal of non-condensable gases during the operation can be identified as one of the major challenges in achieving the targeted power output from this type of ORC systems.

1. Introduction

Organic Rankine Cycles (ORC) are similar to conventional Rankine cycles with the exception that an organic fluid is used as the working fluid. The use of ORCs enables to design small-scale power systems capable of operating at relatively low temperature levels [1]. ORC technology has been proven to be commercially viable especially in geothermal and biomass power plants [1], while the use of ORC in heat recovery applications has attracted increasing interest in recent years [1,2]. Previous studies e.g. [3–6] have investigated the use of ORCs for recovering waste heat from reciprocating engines showing the potential of using ORCs for recovering waste heat from both small- and large-scale engines, and discussed on the critical design aspects of this type of heat recovery systems. Another potential application has been identified as exhaust gas recovery from gas turbines [7–9]. In addition, interest in the use of small-scale ORCs, ranging from 1 kW to 20 kW, in other applications such as the use of ORCs as domestic power units [10,11] has been on the rise in recent times.

The selection of a suitable working fluid is one of the most important steps in the design of ORC systems, as it significantly impacts the performance of the cycle as well as the optimal cycle configuration and dimensions of the process components. Based on the shape of the vapor saturation curve on a temperature-entropy diagram, working fluids can be classified into three categories: dry fluids, isentropic fluids, and wet fluids [12,13]. In ORC systems the fluids having a dry expansion are often preferred [1]. When one selects a working fluid for an ORC, issues related to thermodynamic performance, expander type and the size of the heat exchangers, as well as condensing pressure and evaporation pressure have to be taken into account [14–16]. There are also several

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Nomenclature

Latin alphabet

h	specific enthalpy, kJ/kg
P	power, kW
p	pressure, bar
q_{m}	mass flow rate, kg/s
T	temperature, °C
U	overall heat transfer coefficient, W/m^2/K
M	molecular weight, kmol/kg
m	mass, kg
n	rotational speed, rpm
v	specific volume, m^3/kg

Greek alphabet

η	efficiency, –
ϕ	heat rate, kW
ε	recuperator effectiveness, –
ω	angular speed, rad/s

Subscripts

avg	average
c	cycle
eV	evaporator
eg	exhaust gas
in	inlet
LMTD	logarithmic mean temperature difference
l	liquid
out	outlet
p	pump
rec	recuperator
s	isentropic
t	turbine
v	vapor
wf	working fluid

Abbreviations

EG	exhaust gas
LUT	Lappeenranta University of Technology
MDM	Octamethyltrisiloxane
OP	operational point
ORC	organic Rankine cycle
PS	plate and shell
WF	working fluid

other important considerations and criteria, such as the thermodynamic and physical properties of the fluid, fluid stability at high temperatures, fluid compatibility with materials, environmental impacts, safety, fluid availability, and price [17].

This study concentrates on small-scale and high-temperature ORCs, meaning that the temperature level of the heat source is above 300 °C which is typical for exhaust gas temperature levels in reciprocating engines. For high-temperature ORC applications, fluids with high critical temperature and high molecular weight, such as heavy hydrocarbons and siloxanes have been identified as potential working fluid candidates in some previous studies [5,7,18]. This type of fluids have suitable thermodynamic properties for regenerative high-temperature ORC applications, including high conversion efficiency and dry expansion in the system expander [5,19,20]. When using a working fluid with a high critical temperature, the temperature and enthalpy drop over the process expander is typically relatively low leading to high expander outlet temperatures, which then favors the use of a recuperator in the system [5,19]. In general, the use of high critical temperature fluids results in a large expansion ratio over the expander, low condensing pressure, and the system can reach a high thermodynamic efficiency in high-temperature applications [21]. These kinds of fluids can be considered as suitable candidates for stationary small-scale ORCs, such as for waste heat recovery from small diesel generators, gas turbines, or externally fired domestic ORCs. However, the use of fluids having a high critical temperature and high molecular weight is not necessarily an optimal choice in moving applications, such as in heavy duty trucks, due to the restricted available space for the process heat exchangers and other components [2]. The thermal and chemical stability of the fluid can be identified as an important fluid selection criteria, particularly in the case of high-temperature ORCs. Erhart et al. [22] carried out an experimental study on working fluid decomposition in 7 large-scale high-temperature ORC plants. Their results indicated that decomposition of the fluid occurred over a long time period, and that the degradation of the fluid was caused by the use of petroleum-based lubricants in the system alongside the high working fluid temperatures in the process.

Different types of expanders have been proposed or considered for small-scale ORCs including different types of turbines [23–25], screw expanders [26], piston expanders [25], or vane expanders [10]. The majority of the small-scale ORC systems adopt a screw or scroll expander instead of a turbine and fluids with relatively low critical temperatures are often favored. However, the maximum pressure ratios over volumetric expanders are limited below 5–15 [27,28] which restricts the achievable cycle efficiency, especially in high-temperature ORC applications [21]. The turbine types considered in ORC systems are typically axial [29,30] or radial [31] turbines. Single-stage turbines have been reported to be capable of reaching pressure ratios over 100 which is typical of high-temperature ORCs using fluids of high molecular complexity and high critical temperature[32,33]. In this project, the temperature difference between the heat sink and exhaust gas is high which results in the use of high pressure ratio in the process and allows to reach high thermodynamic efficiency for the cycle.

Based on a literature review of small-scale ORCs, the most of the research efforts have been concentrating on the use of fluids having a relatively low critical temperature and low pressure ratio in the process. Thus, there exists only a limited amount of available experimental data concerning the use of high molecular weight and high critical temperature fluids in small-scale ORC applications. In this paper, the working fluid selection and experimental results of a small-scale high-temperature and high pressure ratio ORC using octamethyltrisiloxane (MDM) as the working fluid are presented. The targeted power level for the ORC in this study is about 10–15 kW that would be suitable especially for waste heat recovery in about 100–200 kW scale engine systems. The aim of this paper is to study especially the performance of the heat exchangers and the capability of the experimental setup to recover the exhaust gas heat. In addition, the potential for producing mechanical power with the studied ORC system was studied and evaluated numerically. Based on the numerical and experimental results, the technical feasibility of this kind of ORC systems and the most critical design aspects are discussed and highlighted.