Energy Conversion and Management 148 (2017) 305–316

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Performance analysis of a new deep super-cooling two-stage organic Rankine cycle

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ARTICLE INFO

*Article history:*
Received 3 October 2016
Received in revised form 19 May 2017
Accepted 1 June 2017

*Keywords:*
High temperature waste heat
Deep super-cooling
Two-stage
Organic Rankine cycle
Effective heat source utilization

ABSTRACT

In this article, a new deep super-cooling two-stage organic Rankine cycle (DTORC) is proposed and evaluated at high temperature waste heat recovery in order to increase the power output. A thermodynamic model of recuperative organic rankine cycle (ORC) is also established for the purpose of comparison. Furthermore, a new evaluation index, effective heat source utilization, is proposed to reflect the relationship among the heat source, power output and consumption of the waste heat carrier. A simulation model is formulated and analysed under a wide range of operating conditions with the heat resource temperature fixed at 300 °C. Hexamethyldisiloxane (MM) and R245fa are used as the working fluid for DTORC, and MM for ORC. In the current work, the comparisons of heat source utilization, net thermal efficiency as well as the total surface area of the heat exchangers between DTORC and RC are discussed in detail. Results show that the DTORC performs better than ORC at high temperature waste heat recovery and it could increase the power output by 150%. Moreover, the maximum net thermal efficiency of DTORC can reach to 23.5% and increased by 30.5% compared with that using ORC, whereas the total surface areas of the heat exchangers are nearly the same.



## 1. Introduction

With rapidly increasing globalization and energy demands, researchers are devoted to seeking opportunities to improve the energy efficiency. Among the energy-efficient technologies, organic Rankine cycle (ORC) is considered as one of the most attractive ways to solve the energy crisis in the future [1]. Over the past two decades, a number of research efforts have been devoted to the studies of ORC on solar thermal [2,3], geothermal [4,5], internal combustion engine (ICE) [6,7], combustion gas turbine [8,9], combined heat and power (CHP) [10], waste heat from power plants [11] and industrial processes [12,13]. For those above application, it is recognized that the heat source temperature is usually in the range of 250–350 °C. Gao et al. [3] developed an ORC system driven by solar energy and the high temperature of the system can be up to 300 °C. Sarkar [14] pointed out that the waste heat at temperatures can be 300–400 °C in some industries such as iron and steel, glass, nonferrous metals, bricks and ceramics processing. Peris et al. [12] summarized the wide range of the waste heat source temperatures from industrial gases and over 60% were in the temperature range of 250–350 °C.

For the case of high temperature waste heat recovery applications, thermal systems should have a high thermal stability requirement against the working fluid. Nowadays, most of the ORC manufacturers [15] and researchers [3,16] are using siloxanes as the working fluids as they have the desired characteristics in reaching high working temperatures and are more thermally stable and environmentally friendly. However, siloxanes are dry organic fluids [17] and have a large sensible heat in isobaric heat discharging sub-process, therefore, recuperative ORC is used in the existing systems. It can significantly improve the thermal efficiency of the system, however, it is difficult to improve the utilization level of the high temperature waste heat sources.

In the ORC system, the inner heat exchanger (IHE) leads to a high exhaust temperature of the waste heat carrier (WHC) [18,19]. The WHC can be a fluid, steam or exhaust gases and often forms an open loop. The IHE only shifts part of the sensible heat in the isobaric heat discharging sub-process from the working fluid to the WHC. This sensible heat will not be converted into power rather will be discharged to the environment carried by the WHC. For a certain waste heat source, ORC system may consume much more waste heat carrier than a basic ORC (BORC) system under the same power output since the BORC can absorb more

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http://dx.doi.org/10.1016/j.enconman.2017.06.006
0196-8904/

**Nomenclature**

| | |
|---|---|
| $h$ | specific enthalpy, kJ/kg |
| $\dot{m}$ | mass flow rate, kg/s |
| $P$ | pressure, kPa |
| $Q$ | quantity of heat, kJ |
| $t/T$ | temperature, °C |
| $W$ | power, kW |
| $Sur_{total}$ | the total surface area of heat exchangers, $m^2$ |
| $\eta_{net}$ | net thermal efficiency, % |
| $\eta_{utilization}$ | heat source utilization, % |

*Greek letters*

| | |
|---|---|
| $\eta$ | efficiency, % |

*Subscripts*

| | |
|---|---|
| *ab* | absorb |
| *c* | critical state |
| *dis* | discharge |
| exp | expander |
| *HTF* | heat transfer fluid |
| *HTFin* | the heat transfer fluid inlet the evaporator |
| *HTFout* | the heat transfer fluid outlet the evaporator |
| *loss* | loss |
| *max1* | the maximum of first stage |
| *max2* | the maximum of second stage |
| *min1* | the minimum of first stage |
| *net* | net |
| *p* | pump |
| *pinch* | pinch point temperature difference |
| *rec* | recuperate |
| *s* | isentropic state |
| *sys* | the whole system |
| *set* | user settings |
| *sur* | surrounding |
| *subcool* | subcooled status |
| *MM* | the MM system |
| *R245fa* | the R245fa system |
| *1-23* | points on plant scheme or in *T-s* diagram |

*Abbreviations*

| | |
|---|---|
| BORC | basic organic Rankine cycle |
| CHP | combined heat and power |
| DTORC | deep super-cooling two-stage organic Rankine cycle |
| EHE | external heat exchanger |
| HTF | heat transfer fluid |
| ICE | internal combustion engine |
| IHE | inner heat exchanger |
| MM | hexamethyldisiloxane |
| MDM | octamethyltrisiloxane |
| ORC | organic Rankine cycle |
| RC | recuperative ORC |
| R245fa | perfluoropropane |
| TORC | two-stage ORC |
| WHC | waste heat carrier |

heat from the unit mass flow rate of the waste heat carrier. In such situations, the extra consumption of the mass flow rate of the waste heat carrier can lead to the resource wastage.

Compared with IHE, the external heat exchanger (EHE) can also take advantage of the heat in the isobaric heat discharging sub-process. EHE can transfer such heat to an extra ORC acting as an evaporator. This system is called two-stage organic Rankine cycle (TORC). Kosmadakis et al. [20] introduced a TORC for reverse osmosis (RO) desalination. In their work the condenser of the high temperature stage acted as the evaporator of the low temperature stage. They used R245fa at high temperature stage and HFC-134a at low temperature stage. Xue et al. [21] proposed a TORC using R227ea and R116 as the working fluids at high and low temperature stage, respectively. Thierry et al. [22] studied the mixtures as the working fluid in TORC, and improved the amount of energy recovery. All these TORC mentioned above are used at low temperature waste heat recovery and have not been applied at high temperature.

Furthermore, how to evaluate the utilization of the heat source and the performance of the thermal systems is also an important issue. Over the past decades, evaluation indexes are mainly concentrated on the economic cost, thermal efficiency and exergy efficiency [23–27]. Some researchers also take the maximum power output as the optimization goal [28,29]. However, few research works take the WHC consumption into account for the performance evaluation. In particular, no evaluation index is available to reflect the relationship among the heat source, power output and WHC consumption. As such, the objective of the current study is to develop a deep super-cooling two-stage organic Rankine cycle (DTORC) based on the traditional TORC with fully utilize the high temperature waste heat and increase the power output. In addition, a new evaluation index, effective heat source utilization, is also defined which will evaluate the ORC systems. The detailed description of DTORC is given in Section 2. The new evaluation index is explained and the thermodynamic models of DTORC and RC are established in Section 3. Finally, the DTORC and RC systems are compared under the same heat source and discussed in Section 4. The three key performance indicators: heat source utilization, net thermal efficiency and total surface area of heat exchangers are compared in a systematic manner.

## 2. System description of DTORC

In the current study, a DTORC system has been developed, as shown in Fig. 1. First, the waste heat is transformed to mechanical energy through the high temperature organic Rankine cycle, this can be regarded as the "high temperature stage". During condensation, the condenser of this high temperature stage will act as the evaporator of the low temperature organic Rankine cycle which is considered as the "low temperature stage".

As the DTORC is used for high temperature waste heat recovery, hexamethyldisiloxane (MM) has been selected for the high temperature stage due to its appropriate thermodynamic properties and optimum thermal stability. The normal boiling point of MM is 100.25 °C. This means the outlet temperature of the high temperature stage turbine can reach 203 °C or higher if the condensation pressure remains positive, as shown in Fig. 2. According to the research of [30], it shows that R245fa is more suitable as the working fluid under such a temperature compared to other working fluids, thus, the refrigerant R245fa has been selected for the low temperature stage. Table 1 lists the characteristics of the working fluids for the DTORC.

In the present work, a new deep super-cooling technology was proposed, as shown in Fig. 3. The sub-process (1-2) is the deep