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Research Paper

Enhancement efficiency of organic Rankine cycle by using sorption system

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HIGHLIGHTS

- Use of sorption cooling to improve the ORC cycle efficiency by reducing the ORC condenser temperature.
- Energy, exergy and economic impacts of the integrating ORC-sorption units are considered.
- Performance curves of the ORC and sorption systems are developed from testing results.
- The optimal ORC-sorption unit is evaluated by projection process.

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ABSTRACT

This paper focuses a method to enhance an organic Rankine cycle (ORC) efficiency by using the sorption systems (absorption and adsorption) for reducing the ORC condenser temperature. Energy efficiency, exergy efficiency and levelized electricity cost (LEC) are used to evaluate the optimal combined unit. Testing data from a 25 kW_e R-245fa ORC prototype, a 1 TR water-LiBr absorption chiller and a 1 TR water-silica gel adsorption refrigeration are tested and analyzed performance curve of each technology to predict thermal performance of the ORC-sorption units at various operating conditions. Projection of the integrating unit of the ORC and sorption systems represent the better energy and exergy efficiencies, when the ORC condenser temperature is decreased. The ORC-absorption efficiencies in terms of energy and exergy increase 7.22%, while the ORC-adsorption system improve 12.46% compared with the normal ORC efficiencies. In economic impact, the LEC of the normal ORC unit is 0.1145 USD/kW h, which is higher than the ORC-absorption unit and the ORC-adsorption unit of 0.1088 USD/kW h and 0.1043 USD/kW h, respectively, at chilled water temperature output the absorption system at 7 °C. Thus, it could be concluded that the ORC-adsorption system is the optimal technique to enhance the ORC electricity generation process in terms of energy efficiency, exergy efficiency and electricity cost.

1. Introduction

An organic Rankine cycle (ORC) is one technology to produce electricity. The ORC system uses organic working fluid as working fluid instead of water in a conventional Rankine cycle. The main advantage point of the organic fluid is boiling point lower than that of water. Various kinds of alternative energy are focused and encouraged for dealing with an increase in the world energy demand, the ratio of renewable energy power plants and reducing carbon dioxide intensity of power generation.

Many studies on the ORC technique were reported. Selection of the ORC working fluid was a popular topic to optimize the suitable refrigerant [1–6]. R-245fa and R-245ca were almost the recommended working fluids for low temperature heat sources. Moreover, the ORC enhancement efficiency is another one of interesting issue. Wang et al. [7] and Li et al. [8] proposed two stage evaporation strategy to improve evaporation process between heat source and working fluid. Eyerera et al. [9] reported experimental study of drop-in replacement refrigerant for low temperature heat. R-1233zd-E was used to improve thermal efficiency in the R-245fa ORC, where R-1233zd-E performs 6.92% better than R245fa. Some studies shown a new design part in the ORC cycle for low temperature heat source such as Jubori et al. [10] developed a small-scale axial turbine and Rohmah et al. [11] presented plate heat exchanger design as condenser. While the integrated modules of a combined organic Rankine-vapor compression refrigeration system [12], an organic Rankine cycle combined with ejector refrigeration [13] and a novel trigeneration system based on organic Rankine cycle installed with heat pumps

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Nomenclature

Abbreviations and symbols

Ac	annual cost (USD/y)
EER	energy efficiency ratio (kWth/kWe)
HHR	heat source and heat sink ratio
LEC	levelized electricity cost (USD/kW h)
P	pressure (bar)
Q	heat rate (kW)
r	discount rate (%)
Inv	investment cost (USD)
t	time (y)
T	temperature (°C)
W	work (kW)

Subscript

A	absorber
AB	absorption system
Ad	adsorber
AD	adsorption system
B	boiler
C	condenser
CW	cooling water
CT	cooling tower
D	desorber
e	electrical power
E	evaporator
Ex	expander
G	generator
HS	heat source
HW	hot water
i	inlet
o	outlet
OP	oil pump
P	refrigerant pump

[14,15] were applied to increase the overall system efficiency. In addition, design of the condensation temperature with respect to the expander characteristics [16,17] and decreasing refrigerant temperature at the ORC condenser by using absorption chiller [18] were carried out.

From the above mentioned literature review, it could be found that many studies reported about the enhancement ORC applications. But, it could be noted that the optimal performance of the sorption systems between the absorption chiller and the adsorption refrigeration integrated with the ORC system for increasing the ORC efficiency did not represent in the recent literatures.

An interesting approach, the method to enhance the ORC cycle efficiency from the sorption systems for reducing the ORC condenser temperature is considered. The experimental results of a R-245fa ORC system, a water-lithium bromide absorption system and a water-silica gel adsorption system are performed to evaluate the optimal integrating system performance. Moreover, the performance curves of the ORC, absorption and adsorption prototypes are evaluated from the testing results to find out the optimal systematic determination of the integrating ORC-sorption unit based on energy efficiency, exergy efficiency and levelized electricity costs.

2. System description

Fig. 1 shows the operating principle of the ORC system. Several working fluids are considered with the ORC cycle such as Hydrochlorofluorocarbon (HCFC) of R-123, Hydrofluorocarbon (HFC) of R-134a and R-245fa including of mixture refrigerants [1–6]. In this study, HFC-245fa is selected because of the main advantage points of low boiling temperature at 15.14 °C, high critical temperature at 154.01 °C, non-corrosive, non-flammable, low-toxicity and friendly environment. Thus the suitable heat source temperature for suppling the ORC system should be higher than 90 °C. Heat source is connected with the ORC cycle at a boiler (Q_B) at point 1 h, which boils R-245fa in liquid phase to be vapor phase at a high pressure (P_{High}) and a boiler temperature (T_B) (point 1). After that heat source leaving the boiler is dropped down fluid temperature at around 15–20 °C at point 2 h. Next, the evaporated working fluid is expanded at a reverse compressor, where is called an expander, to release a mechanical work (W_{Exp}) at point 2. A special twin screw expander is specially designed for coupling with a generator to convert heat to power. The rotor of twin screw expander operates at 8000 rpm for feeding power and driving a reduction gearbox, which the output speed is set at 3000 rpm. The expander is then directed to the generator for generating electricity (W_{ORC}) by the reduction gearbox. In the expander-generator set, a lubrication system is used to reduce friction of the expander. At point 2, lubrication oil and vapor refrigerant are mixed and sent to an oil and vapor separator for dividing the oil and refrigerant fluids at points 3 and 6. Liquid lubrication is feed back to the expander by an oil pump (W_{OP}) (points 4–5). After that, the refrigerant vapor is then condensed in a condenser (Q_C) by heat sink (points 1c-2c) to a low pressure (P_{Low}) and a condenser temperature (T_C) at point 7. The fluid at liquid state is compressed by a refrigerant pump (W_P) to a high pressure (P_{High}) at point 8 and the new cycle restarts. From the above cycle, the ORC energy and exergy efficiencies can be defined by Eqs. (1) and (2), respectively.

$$\eta_{ORC} = \frac{W_{ORC} - W_{OP} - W_P}{Q_B} \tag{1}$$

$$\psi_{ORC} = \frac{W_{ORC} - W_{OP} - W_P}{Ex_B} \tag{2}$$

Exergy rate (Ex_B) from heat transfer is always smaller than heat transfer rate (Q_B), because the fluid temperature ($T_{HW,B,i}$) is considered compared with the reference environment temperature (T_0) as shown in Eq. (3).

$$Ex_B = Q_B\left(1 - \frac{T_0}{T_{HW,B,i}}\right) \tag{3}$$

Fig. 2 shows the operating procedure of the ORC-absorption unit, which the absorption system is used to produce cooled water ($T_{CW,E,o}$) at temperature lower than 15 °C for reducing the working fluid temperature at the ORC condenser (T_C). Rejected heat from the ORC cycle (point 2h) at temperature around 70–90 °C is combined with the absorption cycle at a generator. Released heat of the generator will drop down temperature to be around 60–75 °C (point 3h). In the generator, a binary liquid mixture is working fluid of the absorption system, which consists of a volatile component (absorbate/refrigerant) and a less volatile component (absorbent). Several type of working pair are introduced from various literatures such as water-lithium bromide solution [19], water-lithium chloride solution [20], ammonia-water solution [21]. In this study, water-lithium bromide solution is chosen because this fluid mixture is optimal for producing cooled water temperature around 5–15 °C. Weak solution of binary mixture is heated at the generator and part of the absorbate (water) boils at a high pressure