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Analysis of a solar Rankine cycle powered refrigerator with zeotropic mixtures

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ABSTRACT

A solar organic Rankine cycle (ORC) powered vapor compression cycle (VCC) for refrigeration is under investigation in this paper. To improve the overall system performance, zeotropic mixtures are proposed to be used in the integrated ORC-VCC system for the first time. A thermodynamic model is developed, and a total of eight pure fluids and five zeotropic mixtures with various compositions are evaluated and compared to identify the best combinations of fluids for yielding high system efficiencies. Besides, the influences of generating temperature, refrigerating temperature, superheating and internal heat exchanger (IHE) in ORC on the system performance are analyzed. For the ORC-VCC operating between −5 and 80 °C, dry fluid R600a shows the highest system efficiency (0.2212) among the pure fluids. For zeotropic mixtures, there exists a composition range within which binary mixtures always show higher system efficiency than the component pure fluids. Mixture R161/R600a with an R161 mass fraction of 0.25 shows the highest system efficiency (0.3089) among all fluids, which is increased by 39.6% and 54.7% comparing with R600a and R161, respectively. Adding IHE in ORC benefits the system efficiency, and the benefit is much more evident for dry fluids. Superheating makes wet fluids become applicable in ORC-VCC, but it becomes ineffective in improving the system efficiency when there is no IHE in system.

1. Introduction

With the development of social economy, the need for cooling and refrigeration shoots up over the years, which contributes to the dramatic increase in the energy consumption worldwide. The application of solar thermal energy to refrigerating process has a great potential in reducing the fossil fuels consumption and alleviating environmental issues. Solar assisted air-conditioning/refrigerating system is particularly attractive to regions where the insolation supply and the need for refrigeration reach to maximum levels at the same period.

Solar thermal energy could be converted into cooling process by use of either the absorption/adsorption refrigeration cycle or the thermo-mechanical cooling system (Zeyghami et al., 2015). Although the single effect absorption chillers are still the dominant technology in solar cooling, interest in thermo-mechanical cooling systems has been revived recently due to the appearance of new efficient and environmentally friendly refrigerants (Park et al., 2015) and advancements in organic Rankine cycle equipment (Quoilin et al., 2011), as well as the slow development in breaking the operating limitations on absorption chillers (Xu et al., 2013).

Organic Rankine cycle powered vapor compression cycle (ORC-VCC) is one of the most common way to fulfill the thermo-mechanically activated cooling production. Comparing with absorption refrigeration cycle and ejector cooling cycle, the ORC-VCC system has advantages such as: ability to convert heat into electricity when cooling is not needed by coupling the expander with an electric generator, and ability to supply cooling in remote area where the grid cannot reach by coupling the expander and the compressor directly.

Great efforts have been devoted to the development of the ORC-VCC system since its concept was proposed. Prigmore and Barber (1975) established and tested the first prototype which used separate power and cooling cycles (termed as separate configuration). The dual fluid system was powered by solar and occupied R113 and R12 as the working fluid in ORC and VCC, respectively. A maximum system COP of 0.5 was obtained with the water temperature at the solar collector outlet being 102 °C. Bu et al. (2013) conducted a performance analysis and working fluids selection of a solar powered ice maker, with the power cycle and cooling cycle operated with the same working fluid (termed as single fluid ORC-VCC). In terms of overall efficiency and ice production capacity, R123 was regarded as the most suitable working

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Nomenclature

COP_{VCC}	refrigeration cycle coefficient of performance (–)
CPRm	refrigeration capacity per unit mass flow rate (kW s kg^{-1})
CFCs	chlorofluorocarbons
HCs	hydrocarbons
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
HFOs	hydrofluoroolefins
IHE	internal heat exchanger
NBP	normal boiling point (°C)
WRm	output net power per unit mass flow rate in ORC (kW s kg^{-1})
SHD	superheating degree (K)
SCD	subcooling degree (K)
c_p	specific heat at constant pressure (kJ kg^{-1} K^{-1})
h	specific enthalpy (kJ kg^{-1})
I	solar radiation intensity (kW m^{-2})
m	mass flow rate (kg s^{-1})
q	vapor quality (–)
Q_{refrig}	refrigerating capacity (kW)
r	latent heat of vaporization (kJ kg^{-1})
s	specific entropy (kJ kg^{-1} K^{-1})
T	temperature (°C)
ΔTg	temperature glide (K)
W	power (kW)
x	mass fraction (–)
η_{ETC}	collector efficiency (–)
η_{ORC}	thermal efficiency of ORC (–)
η_{oval}	overall system efficiency (–)
η_s	isentropic efficiency
ζ	superheating parameter (–)

Subscripts

0	ambient
crit	critical
cond	condenser, condensing
evap	evaporator, evaporating
exp	expander
in	inlet
m	mean
out	outlet

fluid for their system. Chang et al. (2017) proposed a hybrid residential micro-CCHP system based on proton exchange membrane fuel cell and solar energy. A dual fluid ORC-VCC with dimethylpentane and R290 being used as the working fluid in ORC and VCC, respectively, was adopted to generate power and cooling/heating simultaneously. To reduce the system complexity, Aphornratana and Sriveerakul (2010) proposed a novel configuration of single fluid ORC-VCC system (termed as integrated cycle) in which the power cycle and cooling cycle shared a common condenser. Three different refrigerants, including R123, R134a and R245ca, were evaluated to find the best candidate for the novel cycle. Wang et al. (2011) attempted to couple the ORC and VCC with a free-piston expander-compressor unit to minimize the power transmission loss and simplify the mechanical design further. The proposed system was able to produce cooling temperature of 0 °C with a low grade thermal energy as low as 60 °C. In addition to the above studies, several other researchers also reported the performance of the ORC-VCC with separate power and cooling cycles either using single fluid (Karellas and Braimakis, 2016; Kim and Perez-Blanco, 2015; Li et al., 2013; Wu et al., 2017; Yılmaz, 2015; Yue et al., 2016) or dual fluid (Molés et al., 2015; Nasir and Kim, 2016; Wang et al., 2011). Generally, the dual fluid ORC-VCC with separate configuration has higher operational flexibility than single fluid system, but it requires better shaft seals to prevent leakages and suction problems between the expansion and compression sections.

The choices of the appropriate working fluid is the most preliminary step of the system design for ORC-VCC. The ideal fluids should meet several basic criteria such as environmental friendliness, safety, stability and energy efficiency. According to the literature review, CFCs (e.g. R113), HCFCs (e.g. R123) and HFCs (e.g. R134a) are the most frequently used working fluids in the previous studies. However, these working fluids either has been, or will be, phased out due to their negative impact on environment. In recent researches, HCs (e.g. R290) and HFOs (e.g. R1234ze) are proposed and investigated as possible alternatives to the CFCs, HCFCs and HFCs. Although HCs and HFOs could be regarded as eco-friendly fluids, flammability and chemical instability become another two arguments against their application in ORC-VCC, respectively. All of the existing studies are focused on pure component working fluids for ORC-VCC system, but it should be pointed out that there are no pure fluids available at present that completely meet all of the criteria.

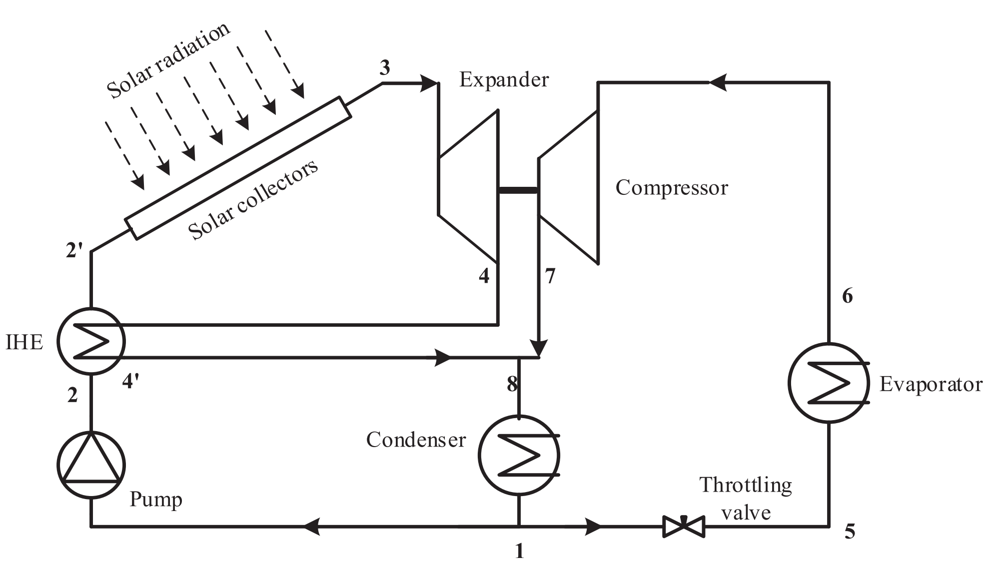

Fig. 1. Schematic diagram of the solar powered ORC-VCC refrigerator.