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Hydrocarbon working fluids for a Rankine cycle powered vapor compression refrigeration system using low-grade thermal energy

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ABSTRACT

As natural fluids, several hydrocarbons with excellent thermophysical properties are recognized as alternative refrigerants to chlorofluorocarbons, hydrochlorofluorocarbons and hydrofluorocarbons. In this paper, the hydrocarbons including propane, butane, isobutane and propylene as working fluids used in an organic Rankine cycle powered vapor compression refrigeration (ORC–VCR) system are analyzed and evaluated. With the overall COP and working fluid mass flow rate of per kW cooling capacity as key performance indicators, the results indicate that butane is the best refrigerant for the ORC–VCR system as the boiler exit temperature is between 60 and 90 °C, the condensation temperature varies from 30 to 55 °C and the evaporation temperature ranges from −15 to 15 °C. When the boiler exit temperature reaches 90 °C and the other input parameters are in typical values, the overall COP of the butane case reaches 0.470.

1. Introduction

With population growth and economy development, currently, the world sees energy and environmental challenges [1]. The utilization of low-grade thermal energy can significantly contribute to reduce the conventional energy consumption and meanwhile to relieve the environmental pollution. In this respect, thermally activated cooling technologies as methods to recover the low-grade thermal energy have gained considerable interest [2].

The thermally activated cooling production can be fulfilled by sorption (absorption and adsorption), desiccant, thermoelectric and Rankine cycle powered vapor compression refrigeration (VCR) systems. Comparing with the others, the last one has flexibility associated with the mechanical power delivered by an expander, which makes the system can continuously utilize the thermal energy throughout the year [3]. In other words, in hot seasons the Rankine cycle powered VCR system can convert all heat into cooling; otherwise, the thermal energy can be converted into electricity [4]. In addition, using thermal energy through a Rankine cycle to activate the VCR cycle makes the technology can be applied in the non-electricity special occasions, e.g. deserts and islands.

The working fluids for the Rankine cycles can be water, ammonia, carbon dioxide or organics. Among them, the organic Rankine cycle (ORC) is preferable for the low-grade thermal energy utilization due to that it has a good efficiency over a wide temperature range [5–7]. The combination of the ORC and VCR cycle is denoted hereafter as the ORC–VCR system. In the past, some efforts have been devoted to the development of the ORC–VCR system. Prigmore and Barber [8] designed and tested an ORC using R113 to drive a VCR system with R12 as refrigerant, and with experimental results they claimed that the system would greatly outperform an absorption refrigeration system when coupled with a concentrating solar collector. Nazer and Zubair [9] and Eğrican and Karakas [10] investigated an ORC–VCR system using R114 and R22 for the power and cooling cycles, respectively, based on thermodynamics. Kaushik et al. [11,12] studied an ORC–VCR system with a regenerative heat exchanger in the ORC. The working fluids in their researches include R12, R22, R113 and R114. Jeong and Kang [13] evaluated three different refrigerants, i.e. R123, R134a and R245ca, for finding the best candidate for the ORC–VCR system. It is found that the R123 case gives the highest thermal efficiency. The work of [13] also indicated that the addition of the recuperator, reheater and economizer can improve the system performance, which is in accordance with the report by Dubey et al. [14] using R245ca for both the power and refrigeration loops. Aphornratana and Sriveerakul [15] analyzed an ORC–VCR system using piston design for the expander and compressor. With R134a as working fluid, they indicated that the system can be powered by low-grade thermal energy as low as 60 °C and produces cooling temperature as low as −10 °C. Wang et al. [3] designed a 5 kW ORC–VCR system with R245fa as working fluid for the power side and R134a as the

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Nomenclature

$\mathrm{COP_{VCR}}$	refrigeration cycle coefficient of performance
$\mathrm{COP_{oval}}$	overall system coefficient of performance
CMR	compression ratio in compressor
EPR	expansion ratio in expander
h_1	enthalpy at expander inlet (kJ/kg)
h_{2s}	enthalpy at expander outlet based on isentropic process (kJ/kg)
h_3	enthalpy at condenser outlet (kJ/kg)
h_4	enthalpy at pump outlet (kJ/kg)
h_{4s}	enthalpy at pump outlet based on isentropic process (kJ/kg)
h_5	enthalpy at evaporator outlet (kJ/kg)
h_7	enthalpy at evaporator inlet (kJ/kg)
h_{6s}	enthalpy at compressor outlet based on isentropic process (kJ/kg)
M	molar mass (kg/kmol)
MkW	working fluid mass flow rate of per kW cooling capacity (kg/(s kW))
m_{ORC}	power cycle mass flow rate (kg/s)
m_{VCR}	refrigeration cycle mass flow rate (kg/s)
NBP	normal boiling point (°C)
ORC	organic Rankine cycle
p_6	pressure at compressor outlet (kPa)
p_5	pressure at evaporator outlet (kPa)
p_{crit}	critical pressure (kPa)
Q_{boil}	boiler heat input (kW)
Q_{evap}	evaporator cooling capacity (kW)
t_{crit}	critical temperature (°C)
v_1	specific volume of working fluid at expander inlet ($\mathrm{m^3/kg}$)
v_2	specific volume of working fluid at expander outlet ($\mathrm{m^3/kg}$)
v_{crit}	critical specific volume ($\mathrm{m^3/kg}$)
VCR	vapor compression refrigeration
W_{comp}	compressor work input (kW)
W_{exp}	expander work output (kW)
W_{net}	net work output (kW)
W_{pump}	pump power consumption (kW)
η_{comp}	compressor isentropic efficiency
η_{exp}	expander isentropic efficiency
η_{pump}	pump isentropic efficiency
η_{ORC}	power cycle thermal efficiency

refrigerant. The overall COP of the system reaches about 0.5, meaning that the system can convert half the amount of waste heat into cooling. Also, Wang et al. [4] investigated the effects of various cycle configurations on the overall system performance. These researches demonstrate the prospect of the ORC–VCR system in the field of heat activated refrigeration.

The literature review also shows that previous ORC–VCR works mainly relate to the chlorofluorocarbons (CFCs, e.g. R113 and R114), hydrochlorofluorocarbons (HCFCs, e.g. R22 and R123) or hydrofluorocarbons (HFCs, e.g. R134a and R245fa). However, with increased environmental awareness these working fluids are now being regulated [16]. As natural fluids several hydrocarbons (HCs) with excellent thermophysical properties are recognized as possible alternatives to the CFCs, HCFCs and HFCs [17]. It is well known that the HCs are environmentally friendly, non-toxic, chemically stable and highly soluble in conventional mineral oil. The only real argument against the application of HCs is flammability, but it should be noted that there are no refrigerants available at present that completely meet the safety, stability, energy efficiency and environmental friendliness [18]. Venkatarathnam and Murthy [18] and Palm [19] indicated that with adequate safety precautions and regulations, the flammability will not pose a major problem in the usage of HCs. One example is isobutane (R600a), which is widely used in the European refrigerator/freezer sector for the past decade and is being used even in Japan and Korea [20]. Thereby, much attention has been dedicated to the application of HCs in the VCR and heat pump systems, such as Bayrakci and Ozgur [21], Ahamed et al. [22] and Chang et al. [23]. Currently, the major HCs under consideration as refrigerants are propane (R290), butane (R600), R600a and propylene (R1270). Some basic properties of the four HCs are given in Table 1.

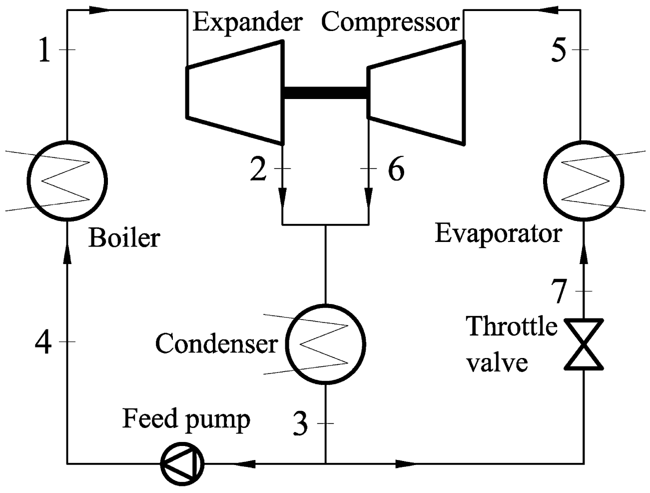

Fig. 1. Schematic diagram of the ORC–VCR system.

Following this introduction, the potentials of four different HCs, i.e. R290, R600, R600a and R1270, used in the ORC–VCR system are evaluated in this paper, and the most promising candidate is recommended. The effects of operating parameters, such as the boiler exit temperature, condensation temperature and evaporation temperature, as well as the expander and compressor isentropic efficiencies, on the performance of the ORC–VCR system are also analyzed and discussed.

2. ORC–VCR system description

The schematic diagram of the ORC–VCR system is shown in Fig. 1. As expected, this system consists of two cycles, i.e. the ORC identified as 1-2-3-4-1 and the VCR cycle as 5-6-3-7-5. This system uses the same working fluid for both the power and refrigeration cycles. The features are that the shafts of the expander in the ORC and the compressor in the VCR cycle are directly coupled; the mechanical power delivered from the ORC through the expander is just enough to drive the compressor and boiler feed pump; and the ORC and VCR cycle share a common condenser.

The T–s diagram of the ORC–VCR cycle is shown in Fig. 2. Accordingly, the various processes of the system are presented as follows:

$1 \rightarrow 2$: actual expansion through the expander;
$1 \rightarrow 2s$: isentropic expansion through the expander;
$2 \rightarrow 3$: heat rejection (condensation) in the ORC;
$3 \rightarrow 4$: actual pumping work;
$3 \rightarrow 4s$: isentropic pumping work;
$4 \rightarrow 1$: heat addition in the boiler;
$3 \rightarrow 7$: isentropic expansion through the throttle valve;
$7 \rightarrow 5$: heat absorption (evaporation) in the VCR cycle;
$5 \rightarrow 6$: actual compression through the compressor;
$5 \rightarrow 6s$: isentropic compression through the compressor;