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Research Paper

Experimental study on a bifunctional heat utilization system of heat pump and power generation using low-grade heat source

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HIGHLIGHTS

- A bifunctional system of power generation and heat pump is analyzed.
- An experimental investigation of the bifunctional scroll machine.
- System performance of ORC power generation mode and heat pump mode is presented.
- Recommendations for the improvement of the bifunctional system.

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ABSTRACT

This paper presents an experimental study on a heat utilization system functioning as power generation and heat pump. The power generation and heat pump functions are achieved on the discipline of organic Rankin cycle (ORC) and reverse Carnot cycle (RCC), respectively. In the experiment, an inverter scroll compressor has been modified to implement dual functions of expansion with power output in power generation mode and compression with power consumption in heat pump mode. The thermodynamic cycles is fed with HCFC-142b and recovering heat from low-grade heat source at temperatures ranging from 50 to 95 °C. The results show good feasibility and stability of the bifunctional system under variable operating conditions. The performance of the bifunctional scroll machine is evaluated in terms of internal filling factor, isentropic efficiency and mechanical efficiency. In ORC power generation mode, the maximum power output is 2.95 kW and thermal efficiency reaches a maximum value of 3.95% at optimal work condition. In heat pump mode, the water temperature at the evaporator inlet is fixed at about 50 °C. The coefficient of performance (COP) ranges from 3.6 to 1.1 when the condensing temperature rises from 75 to 96 °C.

1. Introduction

In the past decades, energy recovery from the low grade heat source (under 100 °C) has become an efficient way to reduce energy consumption and improve efficiency of energy utilization. Power generation based on organic Rankine cycle (ORC) system and heat pump based on reverse Carnot cycle have been two important technologies for recovering heat from low-temperature heat source such as solar energy, geothermal energy and industrial waste heat. The ORC technology transforms heat to power and it is advantageous for low investment and maintenance cost, less complexity, smaller scale and higher reliability and flexibility [1]. The heat pump technology can improve the energy quality from the low-grade heat without changing the form of the energy. In some applications, one single technology is restricted to realize heat utilization for the reason that the temperatures of heat source are out of the operational range or the users' demands are changed. For example, in the solar-assisted heat pump for heating system, the heat pump system is stopped running in non-heating seasons. However, in non-heating seasons, the quality of the heat source is usually higher for strong solar radiation and it is beneficial economically and environmentally to apply ORC power generation system to utilize this heat. The commercial equipment for ORC power generation and heat pump of different types are available in the market. But it has not been seen that one machine set can realize dual-functions of power generation and heat pump.

Scroll machines are commonly used as the expanders in ORC power generation system or compressors in vapor-compression

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Nomenclature

ORC	organic Rankine cycle
RCC	reverse Carnot cycle
EXV	electronic expansion valve
COP	coefficient of performance
rpm	rotations per minute
t	temperature (°C)
P	pressure (bar)
W	power (kW)
Q	heat transfer rate (kW)
M	mass flow rate (kg/s, t/h)
h	specific enthalpy (kJ/kg)
N	rotary speed
V	volume flow rate (m^3/s)
c_p	constant-pressure specific heat (kJ/kg/K) of water

Greek symbols

η	efficiency
φ	filling factor
r	pressure ratio

Subscripts

el	electricity
in	inlet
out	outlet
is	isentropic
eV	evaporator
cond	condenser
com	compression
exp	expansion
hw	hot water
cw	cooling water
wf	working fluid
p	pump
th	thermal
net	net power

heat pump system. The scroll machines have the advantages for its reliability, compact structure, fewer moving parts, lower level of noise and vibration [2].The scroll expanders can be achieved by modifying the commercial scroll compressor including open-drive scroll compressor [3–6] and hermetic refrigerant scroll compressor for heat pump or air conditioning [7–9]. Lemort et al. [5] tested a scroll expander that was originally an open-drive oil-free air scroll compressor. The only modification was to remove the cooling fan and to insulate the machine. The results pointed out that the internal leakages and, to a lesser extent, the supply pressure drop and the mechanical losses are the main losses affecting the performance of the expander. Declaye et al. [6] presented an experimental characterization of an open-drive scroll expander integrated into an Organic Rankine cycle using R245fa as working fluid. Due to the low friction losses in the open-drive expander, the isentropic efficiency could reach 75.7%. Ayachi et al. [9]described the work processed on a permanently oiled hermetic scroll expander as a candidate for small-scale ORC prototypes. The developed semi-empirical model pointed that the performance was degraded when the pressure ratio derived from the built-in volume ratio.

The selections of working fluid for ORC power generation system and heat pump system are another important issue because they have large influence on system performance. There are some organic fluids that are applicable for both of the ORC system and heat pump system, such as R245fa, R245ca, R600a, R134a, R152a, HCFC-142b. Pan et al. [10] selected several working fluids which had excellent performance and were environment friendly for moderately high temperature heat pump. Among the working fluid, HCFC-142b showed better performance with much lower cycle pressure ratio and higher COP. Blaise [11,12] tested HCFC-142b on industrial components and results showed that it can warm air or water up to 90 °C from heat source between 30 and 50 °C. Meanwhile, HCFC-142b used as the working fluid in ORC system can be seen in previous study [1,13–15]. Hærvig et al. [13] proposed guidelines to choose the optimal working fluid based on the heat source available. HCFC-142b showed its feasibility for heat source between 60 and 100 °C. Ustaoglu et al. [14] and Maizza et al. [15] investigated the performance of organic Rankine cycles using HCFC-142b powered by waste energy sources. It is found that HCFC-142b had better efficiency in case of higher evaporating pressure and lower condensing pressure.

Based on the fact that the ORC system and heat pump system have similar structure of main components, some common working mediums and possibility of integrating expansion and compression functions into one machine, it is expected to design a compound system to implement the two functions of power generation and heat pump. This system can enlarge the temperature range of the available heat source and reduce the investment cost compared with two separate devices. Therefore, the compound system is especially suitable for the application where it is difficult for one single function to cover the temperature range of variable heat source and to meet the users' multiple demands.

This paper presents an experimental study of the compound system implementing power generation and heat pump. The rest of the paper is organized as follows. In Section 2, the theoretical cycles are analyzed and thermodynamic equations are proposed for performance analysis. Section 3 introduces the test bench and the experiment procedure. Experimental results are discussed in Section 4. In the last section, main conclusions are drawn.

2. Analysis of the thermodynamic cycles

The T-S diagram of the theoretical cycles is shown in Fig. 1. The functions of power generation and heat pump are realized on the discipline of organic Rankine cycle (cycle 1-2-3-4-5-1) and reverse Carnot cycle (cycle a-b-c-d-a) respectively. Comparing the two cycles, both of them have two isobaric heat transfer processes in the evaporator and condenser. The expansion process (state 1 to 2) in ORC and compression process (state b to c) in RCC are reverse. The isentropic expansion and compression are denoted by process 1 to 2_s and process b to c_s respectively. After the condensation process, the liquid state of the working fluid is pumped to the evaporator at high pressure in ORC system (state 3 to 4). On the contrary, in RCC system, the liquid state of the working fluid undergoes the throttling process to low pressure (state d to a). HCFC-142b is selected as the working fluid for both of the ORC system and RCC system. The thermal properties of HCFC-142bare presented in Table 1.

To analyze the system performance, some thermodynamic equations are presented. For simplified calculation, some assumptions are given as the following: