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Investigation on an innovative cascading cycle for power and refrigeration cogeneration

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ABSTRACT

In order to further realize efficient utilization of low grade heat, an innovative cascading cycle for power and refrigeration cogeneration is proposed. Pumpless Organic Rankine Cycle (ORC) acts as the first stage, and the refrigerant R245fa is selected as the working fluid. Sorption refrigeration cycle serves as the second stage in which silica-gel/LiCl composite sorbent is developed for the improved sorption characteristic. The concerning experimental system is established, and different hot water inlet temperatures from 75 °C to 95 °C are adopted to investigate the cogeneration performance. It is indicated that the highest power and refrigeration output are able to reach 232 W and 4.94 kW, respectively under the condition of 95 °C hot water inlet temperature, 25 °C cooling water temperature and 10 °C chilled water outlet temperature. For different working conditions, the total energy and exergy efficiency of the cascading system range from 0.236 to 0.277 and 0.101 to 0.132, respectively. For cascading system the exergy efficiency of heat utilization ranges from 30.1% to 41.8%, which is 144% and 60% higher than that of pumpless ORC and sorption chiller when the hot water inlet temperature is 95 °C.

1. Introduction

The relationship between energy supply and demand determines the profiles of global development of human activity [1]. Energy conversion technologies especially power generation and refrigeration technologies driven by low grade heat are two major research hotspots, which have drawn burgeoning attentions in recent decades [2,3]. In order to further realize the efficient utilization of the low temperature heat source, different thermal driven power generation and refrigeration cycles are selected and combined with various forms [4,5]. One feasible method is to cascade different cycles in accordance with their temperature gradient [6].

Thermal driven power generation cycles usually require the higher driven temperature, which are suitable as the first stage in a cascading cycle. Among various selections of power generation cycles, Organic Rankine Cycle (ORC) characterized as high reliability, easy maintenance and simple structure is considered to be an effective way to recover low temperature heat, which is common to be combined with other cycles [7,8]. Ejectors were attempted to be integrated with ORC for extra cooling effect. It was indicated that mixture isobutene/pentane of the cogeneration system could reach the highest exergy efficiency of 7.83%. The generation temperature had the greatest influence on exergy efficiency [9]. Compressor of vapour compression refrigeration system was investigated to be connected with the expander of ORC to realize power and cooling cogeneration. It was noted that the total exergy efficiency was able to reach 0.66 [10]. Besides, Mohanty et al. [11] investigated the cascading system which was composed of ORC system and absorption chiller. The cooling effect was produced for the end user without electricity input, thus improving the overall system efficiency. Jiang et al. [12] cascaded ORC with two-stage sorption freezing cycle for joint effect of power and freezing. Results demonstrated that exergy efficiency of heat utilization could be improved to 20.4–29.1% in term of different heat source temperatures. Considering for small cascading systems with ORC as the first stage, fluid pump as a main component will inevitably consume a large part of power, which has a negative effect on energy efficiency and system compactness [13,14]. Therefore, pumpless ORC with a higher performance could be an alternative selection as the first stage for small-scale cascading cycles [15,16].

Thermal driven refrigeration cycles, especially sorption refrigeration cycles are suitable for the construction of the second stage of the cascading cycle due to its lower driven temperature and good adaptability to heat source [17]. Silica gel-water working pair has been extensively investigated for sorption refrigeration since the driven temperature is as low as 60 °C [18,19]. Shanghai Jiaotong

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Nomenclature

C	specific heat, kJ/(kg K)
COP	coefficient of performance
E	exergy, kW
HX	heat exchanger
h	specific enthalpy, J/kg
M	mass, kg
m	mass flow rate, kg/s
P	pressure, Pa
ORC	Organic Rankine Cycle
Q	heat transfer rate, kW
S	entropy, kJ/(kg K)
SCP	specific cooling power, W/kg
T	temperature, K
t	time, s
W	power, W

Greek letters

η	energy and exergy efficiency

Subscripts

ave	average
chi	chilled water
cycle	cascading cycle
en	energy
eva	evaporator
ex	heat exergy
exc	heat exchanger
exp	expander
h	heat
heat source	heat source
hw	hot water
in	inlet
liq	liquid
m	metal
mid	middle state
out	outlet
ref	refrigerant
sat	saturated state
w	water

university successfully designed a small-scale silica gel-water sorption chiller which was displayed at 2010 Shanghai World Expo [20]. Besides, Pan et al. [21] investigated a silica gel-water sorption chiller with modular adsorbers. It was indicated that cooling power, COP and SCP could reach 42.8 kW, 0.51 and 125.0 W/kg, respectively. To further lower the driven temperature, Saha et al. [22] investigated a three-stage silica-gel/water sorption chiller which could supply cooling power with the lowest heat source temperature of 50 °C. To further improve the performance of sorption chiller, novel silica gel/$CaCl_2$ composite sorbent was developed and investigated. Results demonstrated that cooling capacity was increased up to 20% when compared with conventional silica gel-water sorption chiller [23]. Novel silica gel/LiCl composite sorbent was also applied in solar-powered sorption ice makers. Results indicated that the highest daily ice production was 20 kg/m^2 when solar collector area was 1.5 m^2 [24]. An prospective cascading cycle with ORC and silica-gel sorption cycle was proposed and analyzed for power and refrigeration cogeneration. Results revealed that total exergy efficiency ranged from 0.56 to 0.74, which could be improved by 10–40% if compared with Goswami cycle for power and refrigeration cogeneration [25].

Nonetheless, with regard to heat source temperature lower than 100 °C, less experimental research is reported for power and refrigeration cogeneration. In this paper, a novel cascading cycle is proposed, in which pumpless ORC and sorption refrigeration cycle are selected as the first and second stage, respectively. Hot water with higher temperature drives pumpless ORC first, then hot water from the outlet of pumpless ORC drives sorption refrigeration cycle, sequentially.

2. Design of the cascading cycle

Fig. 1 indicates schematic diagram of the cascading cycle for power and refrigeration cogeneration, which is composed of two parts. The first part is pumpless ORC with R245fa as the working fluid, and the second part is silica-gel/LiCl-methanol sorption refrigeration cycle. Pumpless ORC mainly consists of two high-efficient heat exchangers i.e. heat exchanger 1(HX1) and heat exchanger 2(HX2), an expander, a generator, a four-way valve for refrigerant and other auxiliary components. Four-way refrigerant valve switches at intervals to play a similar role with fluid pump when compared with conventional ORC. The expander and generator are connected for integration. Sorption refrigeration cycle mainly consists of two adsorbers, a condenser, an evaporator and six refrigerant valves.

Also worth noting that two thermal driven cycles are connected by the heat exchange fluid pipelines. Four four-way valves for hot and cooling water are used for switching. Heat source supplies the heat through hot water pipelines whereas cooling tower takes away the heat through cooling water pipelines. Hot water first flows to ORC and then flows to sorption refrigeration cycle, which cascades two separated cycles. Under this scenario, low temperature heat could be recovered successively to further improve the efficiency of heat utilization. Consequently, power and cooling effect are able to be obtained by this working process. The circuit of chilled water is used to transport the cooling power out of the evaporator.

Fig. 2 indicates thermodynamic diagram of the cascading cycle, and *T-S* diagram of pumpless ORC and *P-T* diagram of sorption refrigeration cycle are manifested in Fig. 2a and b, respectively.

For pumpless ORC as shown in Fig. 2a, working procedure can be classified into two processes. One is preheating process. The other is power generation process. Power is only produced in the second process, and preheating process is used for switching the valves. The details are illustrated as follows:

(1) In the preheating process, HX1 works as an evaporator while HX2 plays a role as a condenser. Four-way water valves 2, 3, 4 and 5 are open as shown in Fig. 1, and all other valves i.e. both water and refrigerant valves are closed. Since four-way valve is composed of four valve group in real system, four-way valve could be completely closed, which is used to simplify schematic diagram of the cascading cycle in Fig. 1. Evaporator full of R245fa undertakes isochoric heating through hot water, which is 5-1 in Fig. 2a. Pressure of HX1 will increase gradually until it reaches saturation pressure of R245fa in accordance with hot water temperature. Meanwhile, working fluid in the condenser is assumed to start as saturated vapour at high temperature and pressure and it proceeds isochoric cooling process which is 2-4 in Fig. 2a as the liquid gradually occurs.