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Investigation on an innovative cascading cycle for power and refrigeration cogeneration

Long Jiang^{a,b,*}, Huitong Lu^a, Ruzhu Wang^a, Liwei Wang^a, Lixia Gong^a, Yiji Lu^b, Anthony Paul
Roskilly^b

^a Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, China

^b Sir Joseph Swan Centre for Energy Research, Newcastle University, Newcastle NE1 7RU, UK

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.

Keywords

Pumpless Organic Rankine Cycle (ORC); Sorption refrigeration; Cascading cycle; Energy and exergy

Nomenclature

* Corresponding author. Tel. +86-21-34206309

Email: maomaojianglong@sjtu.edu.cn (L. Jiang)

	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
26	Greek letters	
	η	energy and exergy efficiency
27	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

28

29 **1. Introduction**

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

37 Thermal driven power generation cycles usually require the higher driven temperature, which are
38 suitable as the first stage in a cascading cycle. Among various selections of power generation cycles,
39 Organic Rankine Cycle (ORC) characterized as high reliability, easy maintenance and simple structure
40 is considered to be an effective way to recover low temperature heat, which is common to be combined
41 with other cycles[7, 8]. Ejectors were attempted to be integrated with ORC for extra cooling effect. It
42 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 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/CaCl₂ 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/m² when solar collector area was 1.5 m² [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% to 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. 1. Schematic diagram of the cascading cycle for power and refrigeration cogeneration.

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 Fig.2b, 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.

(2) In the power generation process, four-way refrigerant valve 1 is open when pressure of HX1 reaches a higher constant level and HX2 reaches a cooler value. Then R245fa with high temperature and

pressure from HX1 goes through the expander and generates power there which is 2-3 in Fig.2a. Power is generated until there is no pressure difference between two heat exchangers. During this process the high pressure R245fa in the evaporator is isobaric heated which is 1-2 in Fig.2a. The exhaust enters the HX2 and it is isobarically condensed into the saturated liquid which is 3-5 in Fig.2a.

Then working conditions of HX1 and HX2 sequentially switch as evaporator and condenser. Four-way water valves 2, 3, 4, 5 and refrigerant valve 1 change the working direction, and hot water starts to heat HX2 and cooling water cools HX1. A next cycle begins, which is similar with the previous preheating and power generation processes.

For sorption refrigeration cycle as shown in Fig.2b, cycle 1-2-5-6-1 is for the working process of methanol, and cycle 1-2-3-4-1 is for the adsorber. The details are as follows: adsorber 1 is heated by the heat source to the desorption phase which is 1-2 in Fig.2b. After that, the refrigerant is desorbed from adsorber 1 and flows to the condenser through the valve F and C which are 2-5 and 2-3 in Fig.2b, respectively. Then the liquid refrigerant flows to the evaporator through a throttle valve D, and temperature will drop which are 5-6 and 3-4 in Fig.2b. Then the refrigerant evaporates and it is adsorbed by adsorber 2, which is cooled by the cooling medium which are 6-1 and 4-1 in Fig.2b. The evaporation of the refrigerant produces the refrigeration effect inside the evaporator. After that, two adsorbers will proceed the mass and heat recovery sequentially to gain the better refrigeration performance which is not displayed in Fig.2b.

For the next cycle adsorber 1 and 2 will swap their roles while the sorption and desorption processes are completed. Then adsorber 2 will serve for desorption function, and adsorber 1 will adsorb the refrigerant from the evaporator for supplying the cooling effect.

Fig. 2. Thermodynamic diagram (a) T - S diagram of pumpless ORC; (b) P - T diagram of sorption refrigeration cycle.

Fig.3 displays the photo and circuit of the cascading system for power and refrigeration cogeneration with the auxiliary equipment. It is indicated that all the apparatus are connected by metal connectors and water pipes, and schematic pipelines are used for better elaboration due to complex layout of the cascading system. The auxiliary equipment is composed of hot water tank, cooling tower and chilled water tank. Hot water tank heated by the electric heater is adopted to simulate the low temperature heat source. Cooling water from a cooling tower is used to compensate the condensation heat of R245fa and methanol. The control unit controls the temperature of hot water, cooling water and chilled water. An Agilent 34972A data collector is also embedded in the control unit to monitor and log the data. R245fa is selected as the working fluid, and scroll expander is adopted for power generation. Silica-gel/LiCl composite sorbent is developed for adsorber and methanol is chosen as the refrigerant for refrigeration.

In order to have an overall profile of the cascading system, the main parameters for the design of the cascading system are indicated in Table 1 in term of heat exchangers i.e. evaporator and condenser, expander as well as adsorber. With regard to the cascading system, 17 kg liquid R245fa is filled in pumpless ORC and 40 kg silica-gel/LiCl composite sorbents are developed for sorption chiller with 20 kg for each adsorber. Four spiral copper pipes are designed for the better evaporation and condensation

of R245fa. The total length of copper pipes inside heat exchangers is about 15 m, which is longer than the required length of 13 m and 10.6 m as shown the designed parameters. An oil-free scroll expander is adopted for power generation with nominal output of 1 kW, which has an expansion ratio of 3.5:1. The row arrangement of copper pipes are adopted for the condenser and evaporator of sorption chiller, and heat transfer performance could be guaranteed with regard to the designed heat transfer coefficient. Flowrate of hot water, cooling water and chilled water are 2 m³/h, 3 m³/h and 0.7 m³/h, respectively.

Fig. 3. The innovative cascading system for power and refrigeration cogeneration.

Table 1. The main parameters for the design of the cascading system

Apparatus	Parameters	Value
Evaporator of pumpless ORC	Total required length of copper pipe (m)	13
	Total heat transfer coefficient (W/(m ² ·K))	4152.8
Condenser of pumpless ORC	Total required length of copper pipe (m)	10.6
	Total heat transfer coefficient (W/(m ² ·K))	3362.3
Scroll expander	Nominal output (kW)	1
	Expansion ratio	3.5:1
R245fa	Total mass (kg)	17
Adsorber	Heat transfer coefficient for sorbent direction (W/(m ² ·K))	50.57
	Heat transfer coefficient for heat transfer fluid direction (W/(m ² ·K))	2856(desorption) /2360(sorption)
Condenser of chiller	Heat transfer coefficient for heat transfer fluid direction(W/(m ² ·K))	5628
	Heat transfer coefficient for steam direction (W/(m ² ·K))	4392
Evaporator of chiller	Heat transfer coefficient for heat transfer fluid direction(W/(m ² ·K))	2392
	Heat transfer coefficient for steam direction (W/(m ² ·K))	1725
Sorbent	Total mass (kg)	40

3. Performance evaluation

Performance evaluation of the cascading system is separated into two parts for further elaboration, which is as follows:

For pumpless ORC system, heat input Q_{h1} is composed of the heat Q_{ref} transferred to R245fa for evaporation and the heat for heating metal part of heat exchanger.

Total heat input of pumpless ORC system:

$$Q_{h1} = Q_{refl} + \frac{1}{t_{cycle}} M_{exc} \cdot C_m \cdot \Delta T_m = \frac{\int_0^{t_{cycle}} C_w \cdot m_w \cdot (T_{h1,in} - T_{h1,out}) dt}{t_{cycle}} \quad (1)$$

where t_{cycle} is the cycle time of the cascading system; $T_{h1,in}$ and $T_{h1,out}$ are the inlet and outlet hot water temperature of pumpless ORC system.

The heat Q_{refl} in equation 1:

$$Q_{refl} = \frac{1}{t_{cycle}} \left[M_{ref} \cdot (h_{eva,mid} - h_{liq,sat}) + \int_0^{t_{power}} m_{ref} \cdot (h_{eva,out} - h_{eva,mid}) dt \right] \quad (2)$$

where $h_{eva,mid}$ is the mid-state enthalpy of the fluid at the point 1 in Fig.2a; $h_{eva,out}$ is the enthalpy of the fluid at the point 2 in Fig.2a; $h_{liq,sat}$ is the enthalpy of the saturated liquid at the point 5 in Fig.2a.

The average power output of the generator:

$$W_{ave} = \frac{1}{t_{cycle}} \int_0^{t_{cycle}} W dt \quad (3)$$

where W is the instantaneous power output.

Energy efficiency of pumpless ORC system:

$$\eta_{en} = \frac{W_{ave}}{Q_{h1}} \quad (4)$$

Heat exergy of pumpless ORC system:

$$E_{ex1} = Q_{h1} \cdot \left(1 - \frac{T_0}{T_{h1,ave}} \right) \quad (5)$$

where $T_{h1,ave}$ is the average temperature of hot water; T_0 is environmental temperature.

Exergy efficiency of the pumpless ORC system:

$$\eta_{ex1} = \frac{W_{ave}}{E_{ex1}} \quad (6)$$

For sorption chiller, heating input for sorption chiller:

$$Q_{h2} = \frac{\int_0^{t_{cycle}} c_w \cdot m_h \cdot (T_{h2,in} - T_{h2,out}) dt}{t_{cycle}} \quad (7)$$

where t_{cycle} is the cycle time; c_w is specific heat of water; $T_{h2,in}$ and $T_{h2,out}$ are the inlet and outlet hot water temperature of sorption chiller.

Cooling power of sorption chiller:

$$Q_{ref2} = \frac{\int_0^{t_{cycle}} c_w \cdot m_{chi} \cdot (T_{chi,in} - T_{chi,out}) dt}{t_{cycle}} \quad (8)$$

where m_{chi} is the mass flowrate of chilled water in the evaporator; $T_{chi,in}$ and $T_{chi,out}$ are the inlet and outlet chilled water temperature.

COP of sorption chiller:

$$COP = \frac{Q_{ref2}}{Q_{h2}} \quad (9)$$

Refrigeration exergy:

$$E_{\text{ex,ref}} = Q_{\text{ref2}} \cdot \left(\frac{T_0}{T_{\text{eva,ave}}} - 1 \right) \quad (10)$$

where $T_{\text{eva,ave}}$ is the average chilled water inlet and outlet temperature of sorption chiller.

Heat exergy:

$$E_{\text{ex2}} = Q_{\text{h2}} \cdot \left(1 - \frac{T_0}{T_{\text{h2,ave}}} \right) \quad (11)$$

where $T_{\text{h2,ave}}$ is the average hot water inlet and outlet temperature of sorption chiller.

Exergy efficiency:

$$\eta_{\text{ex2}} = \frac{E_{\text{ref2}}}{E_{\text{ex2}}} \quad (12)$$

For the overall performance of the cascading system, the total energy efficiency and exergy efficiency of the cascading system:

$$\eta_{\text{tot,en}} = \frac{Q_{\text{ref2}} + W_{\text{ave}}}{Q_{\text{h1}} + Q_{\text{h2}}} \quad (13)$$

$$\eta_{\text{tot,ex}} = \frac{E_{\text{ex,ref}} + W_{\text{ave}}}{E_{\text{ex1}} + E_{\text{ex2}}} \quad (14)$$

Exergy efficiency of heat utilization of the cascading system:

$$\eta_{\text{heat source}} = 1 - \frac{(T_{\text{in}} - T_0) \times (1 - \frac{T_0}{T_{\text{out}}})}{(T_{\text{out}} - T_0) \times (1 - \frac{T_0}{T_{\text{in}}})} \quad (15)$$

4. Experimental results and discussions

In order to investigate the overall performance of the cascading system, different hot water temperatures from 75°C to 95°C are employed with 5°C increment while cooling water temperature is 25°C i.e. environmental temperature. Cycle time of cascading system is selected as 10 minutes. Power generation process and sorption refrigeration process will simultaneously proceed in a cogeneration cycle, in which both power and cooling effect could be obtained.

Fig.4 shows different inlet and outlet temperatures of hot water as well as their temperature

differences. When hot water inlet temperature of the cascading system ranges from 75°C to 95°C, hot water outlet temperature of pumpless ORC ranges from 71.03°C to 91.98°C. The temperature is a little higher than that of the inlet temperature for sorption chiller due to the pipe temperature drop, which ranges from 70.57°C to 90.48°C as shown in Fig.4a. Besides, when hot water inlet temperature of cascading cycle is 95°C, temperature drop of hot water temperature for the inlet and outlet of the cascading cycle is 11.52°C, and the values for pumpless ORC and sorption chiller are 4.02°C and 7°C, respectively which are shown in Fig.4b. Temperature difference of the cascading cycle is improved effectively, which will further improve the exergy efficiency of heat utilization effectively.

(a)

(b)

Fig. 4. Hot water temperature for cascading cycle (a) inlet and outlet temperature; (b) temperature difference.

Since temperature trends under different working conditions are similar, 95°C hot water inlet

temperature is selected as an example for further illustration. Fig.5 manifests hot water, cooling water inlet and outlet temperature of pumpless ORC. As Fig.5 shows, temperature trends are similar between two heat exchangers, which indicates the good system stability. In the preheating process hot water inlet and outlet temperature first declines sharply. Hot water outlet temperature drops from 95°C to 57°C, and simultaneously cooling water outlet temperature climbs from 25°C to 29.7°C. When the preheating process happens, cooling water originally inside HX2 is required to be flow away. Then the heat is consumed for sensible heat, which accounts for heating the metal part of heat exchanger from low temperature to high temperature. Besides, the other certain amount of heat accounts for heating the sub-cooled refrigerant liquid of R245fa to saturated state. Also worth noting that hot water outlet temperature declines slightly when power generation process begins. The reason is mainly because most of R245fa has the enough heat transfer area and begins to evaporate.

The real working processes are much different from that shown in the theoretical T - S diagram, which are not always stabilized due to the heat exchanging between R245fa and hot water in the heat exchanger. When power generation process starts, R245fa requires a large quantity of heat for evaporation. Besides, two heat exchangers are almost symmetrical whenever the power generation process starts or preheating process starts, which indicates a good match among different working cycles.

Fig. 5. Hot water, cooling water inlet and outlet temperature vs. time.

Fig.6 demonstrates the maximum power output and the highest inlet pressure of the expander when

hot water inlet temperature ranges from 75°C to 95°C. It is indicated that the highest power output is able to reach 232 W when hot water inlet temperature is 95°C. For different hot water inlet temperatures from 75°C to 95°C, the maximum power output ranges from 103 W to 232 W. When hot water inlet temperature increases, the inlet pressure of the expander will accordingly increases, which leads to the higher power output of the system.

Fig. 6. The maximum power output and the highest inlet pressure vs. hot water inlet temperature.

On the basis of Fig.5 and Fig.6, energy efficiency and average power output of pumpless ORC system under the condition of different hot water inlet temperatures are analyzed which are shown in Fig.7. Results show that power output increases with the rise of hot water inlet temperature while energy efficiency first increases and then decreases with the increase of hot water inlet temperature. For different hot water inlet temperatures from 75°C to 95°C, energy efficiency ranges from 1.61% to 1.9% and the average power output ranges from 74.7 W to 115.7 W. The higher hot water inlet temperature is correlated with the less time lasted. This is mainly because the higher temperature accelerates the heat transfer process, which results in a larger mass flow rate. In the experiment, the time for the pre-heating process is controlled as 1 minute. The time for power generation varies from 7 minutes to 9 minutes which is

determined by the external conditions. To match the sorption chiller, power generation process will be adjusted and equalized to the cycle time of the cascading system.

Fig.8 indicates heat exergy and exergy efficiency of pumpless ORC. It is indicated that exergy climbs linearly with the increment of hot water inlet temperature. Different from heat exergy of the system, exergy efficiency decreases gradually from 75°C to 95°C. That is because exergy efficiency is related with not only the power output and heat exergy but also the time of power generation and valve switching. Since hot water inlet temperature is low, heat exergy is not relatively high. Heat exergy ranges from 0.6 kW to 1.34 kW when hot water inlet temperature from 75°C to 95°C. The highest exergy efficiency is able to reach 12.6% when hot water temperature is 75°C. For different hot water inlet temperatures, exergy efficiency ranges from 8.7% to 12.6%.

Fig. 7. Energy efficiency and average power output of pumpless ORC vs. hot water inlet temperature.

Fig. 8. Exergy and exergy efficiency of pumpless ORC vs. hot water inlet temperature.

Errors of energy and exergy efficiency of pumpless ORC system can be evaluated according to the equation 16 and 17. The largest error of energy efficiency and exergy efficiency of pumpless ORC system are 5.2% and 11.6%, respectively.

$$\Delta\eta_{en} = \sqrt{\left(\frac{\partial\eta_{en}}{\partial W_{ave}} \Delta T_{ave}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial T_{h1,in}} \Delta T_{h1,in}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial T_{h1,out}} \Delta T_{h1,out}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial m_w} \Delta m_w\right)^2} \quad (16)$$

$$\Delta\eta_{ex} = \sqrt{\left(\frac{\partial\eta_{ex}}{\partial W_{ave}} \Delta T_{ave}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial T_{h1,in}} \Delta T_{h1,in}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial T_{h1,out}} \Delta T_{h1,out}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial m_w} \Delta m_w\right)^2} \quad (17)$$

Sorption chiller as the second stage of cascading system should also match pumpless ORC with respect to hot water inlet temperature and cycle time. The hot water inlet temperature of sorption chiller ranges from 70.57°C to 90.48°C. As mentioned above, time for power generation process is about 9 minutes while the preheating time is about 1 minute, which is almost equal to the required heat and mass recovery time[26]. Therefore, cycle time of sorption chiller is also set as 10 minutes, in which 1 minute is spent for heat and mass recovery. The remaining 9 minutes are for desorption/refrigeration process.

Since temperatures of sorption chiller under different working conditions are similar, 85°C hot water

inlet temperature, 25°C cooling water inlet temperature and 10°C chilled water outlet temperature are exemplified for further illustration. Fig.9 shows temperatures of hot water, cooling water, and chilled water with the time. It is worth noting that hot water outlet temperature from the silica-gel/LiCl-methanol sorption chiller decreases remarkably at the beginning of the cycle. This is mainly because the metal part and composite sorbent are required to be heated. During mass recovery process, hot water outlet temperature decreases, and hot water is bypassed in the heat recovery. Cooling water outlet temperature also increases sharply at initial stage, then decreases and increases again. Chilled water outlet temperature firstly declines remarkably and increases as the time goes by. The reason is mainly because the sorption rate is large at first and later tends to become smaller due to the sorption reaction characteristic.

Fig. 9. Temperature of hot water, cooling water and chilled water vs. time.

Fig.10 indicates cooling power and COP of sorption chiller under the condition of the different hot water inlet temperatures. It is demonstrated that performance of sorption chiller is influenced by hot water inlet temperature from 70.57°C to 80.53°C, and then followed by a slight decline. Therefore, the suitable temperature is about 80°C since system performance almost doesn't change much with temperature higher than 80°C. For different hot water inlet temperatures from 70.57°C to 90.48°C, cooling power and COP range from 3.56 kW to 4.94 kW and 0.319 to 0.41, respectively. The exergy and

exergy efficiency of sorption chiller are also analyzed as shown in Fig.11. Again because hot water inlet temperature is relatively low, heat exergy is much lower than the heat, which ranges from 1.46 kW to 2.2 kW. Heat exergy increases with the increase of hot water inlet temperature while exergy efficiency increases at first and declines gradually. For different hot water inlet temperatures from 70.57°C to 90.48°C, exergy efficiency ranges from 11.8% to 14.3%.

Fig. 10. Cooling power and COP of sorption chiller vs. hot water inlet temperature.

Fig. 11. Exergy and exergy efficiency of sorption chiller vs. hot water inlet temperature.

Errors of energy and exergy efficiency of sorption chiller could be evaluated according to the equation 18 and 19. It is indicated that the largest errors of COP and exergy efficiency of sorption chiller

are 9.13% and 11.33%, respectively, when hot water inlet temperature is 90.48°C.

$$\Delta COP = \sqrt{\left(\frac{\partial COP}{\partial T_{h2,in}} \Delta T_{h2,in}\right)^2 + \left(\frac{\partial COP}{\partial T_{h2,out}} \Delta T_{h2,out}\right)^2 + \left(\frac{\partial COP}{\partial T_{chi,in}} \Delta T_{chi,in}\right)^2 + \left(\frac{\partial COP}{\partial T_{chi,out}} \Delta T_{chi,out}\right)^2 + \left(\frac{\partial COP}{\partial m} \Delta m\right)^2} \quad (18)$$

$$\Delta \eta_{ex} = \sqrt{\left(\frac{\partial \eta_{ex}}{\partial T_{h2,in}} \Delta T_{h2,in}\right)^2 + \left(\frac{\partial \eta_{ex}}{\partial T_{h2,out}} \Delta T_{h2,out}\right)^2 + \left(\frac{\partial \eta_{ex}}{\partial T_{chi,in}} \Delta T_{chi,in}\right)^2 + \left(\frac{\partial \eta_{ex}}{\partial T_{chi,out}} \Delta T_{chi,out}\right)^2 + \left(\frac{\partial \eta_{ex}}{\partial m} \Delta m\right)^2} \quad (19)$$

5. Overall performance evaluation

5.1 Energy and exergy efficiency of the cascading system

Fig.12 shows total energy and exergy efficiency of the cascading system for power and refrigeration cogeneration under the condition of different hot water inlet temperatures from 75°C to 95°C. Performance of the cascading system is compared with that assessed by separated performance of each system. It is worth noting that performance of the cascading system is lower than that calculated by each system, especially for total exergy efficiency. It is not accurate to evaluate the total cascading system by using performance of each system. In fact, electricity produced by pumpless ORC system is much higher than that of the cascading system due to the fact cycle time selected for the cogeneration process is not the optimal time for power generation. Cascading two systems will have the influence on inlet and outlet temperature, flowrate and cycle time, which will inevitably suffer some losses when compared with the accumulated performance of each separated system.

As Fig.12 shows, for hot water inlet temperature from 75°C to 95°C, 25°C environmental temperature and 10°C chilled water temperature, total energy efficiency and exergy efficiency of the cascading system for power and refrigeration cogeneration range from 0.236 to 0.277 and 0.101 to 0.132, respectively. The largest difference of energy and exergy efficiency between the cogeneration system and separated system are able to reach 3.2% and 20%. Since power output is not relatively high, cooling

power still takes a leading role as the main output of the cogeneration system. This is the reason why the energy efficiency shows the similar trend as performance of sorption chiller. Nonetheless, power produced by pumpless ORC is enough for the consumption of sorption chiller.

Fig. 12. Total energy and exergy efficiency vs. hot water inlet temperature.

It is widely acknowledged that power enjoys the higher energy grade than that of refrigeration. If power is transfer into the same dimension as refrigeration by defining COP, it will be different scenario by using this evaluation method. For air-conditioning condition, COP is normally defined as 4 to 5. Energy efficiency of the cascading system with different evaluation methods is demonstrated as shown in Fig.13. It is noted that the system performance with new evaluation method is improved remarkably when compared with the previous evaluation method. For different hot water inlet temperatures from 75°C to 95°C, total energy efficiency ranges from 25.4% to 29.9%, which is improved by up to 8.1%.

Fig. 13. Total energy efficiency of the cascading system by using different evaluation methods.

Errors of energy and exergy efficiency of the cascading system for power and refrigeration cogeneration can be assessed according to the equation 20 and 21. The largest error of energy efficiency and exergy efficiency are 10.3% and 13.2%, respectively.

$$\Delta\eta_{en} = \sqrt{\left(\frac{\partial\eta_{en}}{\partial W_{ave}} \Delta W_{ave}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial T_{chi,in}} \Delta T_{chi,in}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial T_{chi,out}} \Delta T_{chi,out}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial T_{h,in}} \Delta T_{h,in}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial T_{h,out}} \Delta T_{h,out}\right)^2 + \left(\frac{\partial\eta_{en}}{\partial m_w} \Delta m_w\right)^2} \quad (20)$$

$$\Delta\eta_{ex} = \sqrt{\left(\frac{\partial\eta_{ex}}{\partial W_{ave}} \Delta W_{ave}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial T_{chi,in}} \Delta T_{chi,in}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial T_{chi,out}} \Delta T_{chi,out}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial T_{h,in}} \Delta T_{h,in}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial T_{h,out}} \Delta T_{h,out}\right)^2 + \left(\frac{\partial\eta_{ex}}{\partial m_w} \Delta m_w\right)^2} \quad (21)$$

5.2 Exergy efficiency of heat utilization

Fig.14 demonstrates exergy efficiency of heat utilization under the condition of different hot water inlet temperatures in term of pumpless ORC, sorption refrigeration cycle and the cascading cycle. The exergy efficiency of heat utilization for pumpless ORC and sorption refrigeration cycle range from 12.3% to 17.6% and from 18.8% to 26.5%, separately. Comparably, for cascading cycle the exergy efficiency

of heat utilization ranges from 30.1% to 41.8%, which is 144% and 60% higher than pumpless ORC and sorption cycle, respectively when hot water inlet temperature is 95°C. Even for the lowest hot water inlet temperature of 75°C, the improvement is still as high as 136.5% and 57.7%, respectively, which indicates great potentials for heat utilization.

Fig. 14. Exergy efficiency of heat utilization vs. hot water inlet temperature.

6. Conclusions

An innovative cascading cycle is investigated and analyzed for power and refrigeration cogeneration to improve the overall heat utilization efficiency of low grade heat. In the cascading cycle, pumpless ORC served as the first stage to supply the power, and sorption chiller plays the role as the second part for refrigeration output. The concerning experimental system is established and analyzed. Conclusions are yielded as follows:

- [1] For pumpless ORC, energy efficiency ranges from 1.61% to 1.9% and the average power output ranges from 74.7 W to 115.7 W under the condition of different hot water inlet temperatures from 75°C to 95°C. Exergy climbs linearly with the increment of hot water inlet temperature. Heat exergy ranges from 0.6 kW to 1.34 kW under the condition of 75°C to 95°C

410 hot water inlet temperature. For different hot water inlet temperatures, exergy efficiency ranges
411 from 8.7% to 12.6%.

412 [2] For silica-gel/LiCl-methanol sorption chiller, cooling power and COP range from 3.56 kW to
413 4.94kW and 0.319 to 0.41, respectively under the condition of different hot water inlet
414 temperature from 70.57°C to 90.48°C. Heat exergy ranges from 1.46 kW to 2.2 kW. Exergy
415 efficiency increases at first and decreases with the increase of hot water inlet temperature,
416 which ranges from 0.118 to 0.143.

417 [3] For the cascading system, the highest power and refrigeration power are 232 W and 4.94 kW
418 when hot water inlet temperature is 95°C. For hot water inlet temperature from 75°C to 95°C,
419 25°C environmental temperature and 10°C chilled water temperature, the total energy
420 efficiency ranges from 0.236 to 0.277 and exergy efficiency range from 0.101 to 0.132.

421 [4] Exergy efficiency of heat utilization for pumpless ORC and sorption chiller range from 12.3%
422 to 17.6% and from 18.8% to 26.5%, separately. In contrast, for the cascading cycle exergy
423 efficiency of heat utilization ranges from 30.1% to 41.8%, which is 144% and 60% higher than
424 pumpless ORC and sorption chiller, respectively, when the hot water inlet temperature is 95°C.
425 Even for the lowest hot water inlet temperature of 75°C, the improvement is still as high as
426 136.5% and 57.7%, separately.

427

428 It is worth noting that power output of pumpless ORC is used for the electricity consumption of
429 sorption chiller such as water pumps to realize real thermal driven refrigeration with no extra electricity
430 input. Such a cascading cycle shows great potentials for the places where the refrigeration is required.
431 Desert and tropical islands will be suitable application sites where electricity is not sufficient. It is

admitted that cooling water temperature will be increased due to the relatively high ambient temperature e.g. 35°C, which will inevitably result in about 15% loss of system performance when compared with the cogeneration performance under the condition of 25°C cooling water temperature in this experiment. One remarkable fact is that there are enough heat source and spaces for the cascading system in the deserts and tropical islands. Cooling power and electricity should be given the priority to other factors such as system performance and compactness. Therefore, cascading system is still a good choice for air conditioning in the remote areas. Also worth noting the cogeneration system could be extensively applied into the places where have enough industrial waste heat with temperature lower than 100°C such as steel factory.

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