

Feasibility of drying system using waste heat as the heating source

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Abstract. In this study, a wastewater heat pump system was proposed and its thermal performance was analyzed. The proposed system includes two evaporators: an air-source evaporator and a water-source evaporator. The air-source evaporator absorbs heat from the moist hot air which exhaust from the drying oven. The water-source evaporator absorbs heat from the waste water, while the waste water recovers heat from the mechanical energy, which was produced by cutting and polishing in stone production. The thermodynamic model was developed to evaluate the performance of the proposed system. The energetic analysis was carried out to investigate the influences of the temperature of fresh air. The results show significantly higher energy efficiency, compact-sized and energy-saving compared with the system which uses air as the heat source. Among the seven of alternative refrigerants (R152a, R123, R1234yf, R1234ze, R600a, R22 and R600) investigated, R123 was suggested to be used in this heat pump for its high heating efficiency, inflammable, very low ODP(Ozone Depletion Potential) and GWP(Global warming potential).

1. Introduction

The industrial drying energy consumption is responsible for 14-35% of the china industrial energy use. Large amounts of low-grade heat were wasted, and cannot be used reasonably. By analysing the existing heat pump drying device, the results show that the problems drying device mainly existed are as follows. Firstly, the mainly heating modes of industrial dryers are electric heating and steam heating. The energy consumption of these drying modes is relatively large, which would cause negative effect on environment. And the drying effect is not as ideal as expected. Secondly, heat pump drying technology used in the domestic and heat pump dryers used in industry are still in the stage of laboratory research [1-4].

The industrial energy is lost as waste heat in the form of hot exhaust gases, cooling water, and the heat lost from hot equipment surfaces. There are two main works in the process of stone production: cutting and polishing. In order to improve the service life of the cutter, the production efficiency and product quality, cooling cutting tools and removing abrasive dust by water during processing are need. Since the stone processing consumes large amounts of water, lots of electric energy was consumed during cutting and polishing, much of the energy was absorbed by wastewater and finally dissipated in the environment. At present, the wastewater treatment equipment of the enterprise is simplified. A

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common way to deal with wastewater flowing from the plant is to pass through several simple sedimentation tanks, or directly discharge into the environment without any treatment. This is not only a waste of valuable water resources, but also causing great damage to the environment and the waste heat energy in the water absorbed from the process of cutting and grinding. The traditional stone drying mainly takes the form of electric heating drying, where all heat is from electricity consumption, and the hot air is discharged into the atmosphere directly after drying. This approach is not only a waste of energy, but also causes serious environmental pollution.

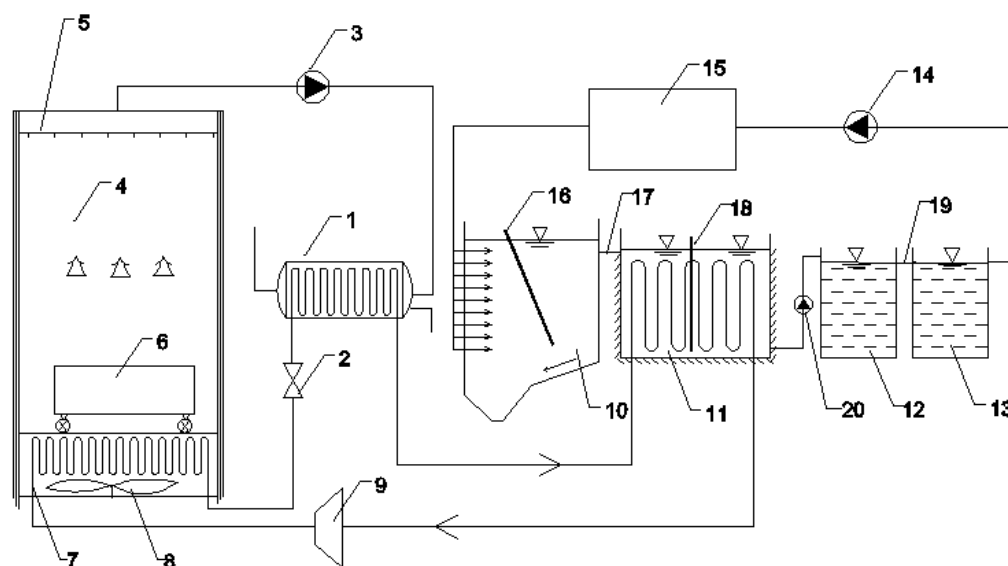
Typically, the electricity power consumed by cutting and grinding, is much higher than the thermal energy required for drying. Analysis and demonstration of the industrial waste heat recovery system, recycling the heat from wastewater and exhaust presented in this article, has higher economy, energy saving and better effect on environment. At the same time, to encourage enterprises recycling wastewater, supporting the construction of settling ponds, reservoirs and circular pool, minimize the consumption of non-renewable energy, and to save operating cost. The main contents are as follows. A wastewater heat pump system was proposed and introduced. Its performance was theoretical analyzed and its feasibility was proved by comparing with conventional air cooling systems. The superior thermal performance with highest COP is found by comparing different substances.

2. The composition and working principles of the system

2.1. The fundamental composition of the system

The system is consisted of three subsystems, namely a wastewater recycling system, a refrigerant cycle system and a hot air heating system, as shown in figure 1.

Refrigerant cycle system evaporator contains two parts: air-source evaporator and water-source evaporator. Air-source evaporator heat transfer process is mainly carried out by the moist hot air at the end of the drying oven, and water-source evaporator is heated by recovering heat from waste water. Low-grade waste heat is converted into high-grade thermal energy by the utilization of wastewater from recycling system, and the energy of the wastewater is recovered by absorbing the mechanical energy from the cutting and grinding. Hot air heating system is an open-loop system, with the fresh air



and exhaust recycling unit.

Figure 1. Schematic illustration of the principal design of the heat recovery system.

Table 1. Illustration of the serial number in figure 1.

Number	Component	Number	Component
1	Air-Source Evaporator	11	Immersed Water-Source Evaporator
2	Expansion Valve	12	Second Settlement Tank
3	Air Pump	13	Cleanwater Storage Tank
4	Drying Oven	14	Water Pump
5	Sieve Plate	15	Cutters And Sanders
6	Vehicle For Material Transportation	16	First Plate
7	Condenser	17	First Overflow Pipe
8	Fan	18	Second Plate
9	Compressor	19	Second Overflow Pipe
10	First Settlement Tank	20	Wastewater Pump

2.2. The working principles of the system

Water temperature rise of stone production is generally 5-8°C with tremendous heat. The wastewater was collected through the irrigation plant in the region, and then pulled into the first settlement tank, so most of the suspended solids sink to the bottom and the supernatant directly flows into immersed water-source evaporator as heat source. The wastewater of lower temperature was pulled into the next settler under the traction of water pump, and its supernatant flowed into the Clearwater storage tank. Eventually, clean water entered the production plant for recycling by water pump.

In the system, the heat pump cycle is consists of a compressor, a condenser, an expansion valve, two evaporators and auxiliary system equipment. The working fluid is refrigerant. The refrigerant enters the condenser as a superheated vapor after compressed, and gives heat to the inlet fresh air which providing the main energy source for the oven dried until it becomes saturated liquid and leaves the condenser. The refrigerant is then throttled to the evaporator pressure while its temperature drops below the wastewater temperature. After it absorbs heat in the evaporator, it leaves as saturated vapor.

The fresh air enters the drying oven after absorbed heat in the condenser, and then heating stones and taking away the water in the materials, so the air temperature reduce and the humidity increase at the same time. Then, the air is discharged into the atmosphere after recovery heat from the oven heat and humid air in the evaporator. Recovering the latent heat in the exhaust need the gas temperature cooled below the dew-point temperature. The air pass through the evaporator for heat recovery to provide the necessary heat for the refrigerant cycle, realization of heat recycling, and make full use of the limited heat.

2.3. The calculation formula

2.3.1. The energy for the drying of stone material.

$$Q = Q_1 + Q_2 + Q_3 \quad (1)$$

$$Q_2 = Cm\Delta T \quad (2)$$

$$Q_3 = mI \quad (3)$$

Here, I , C , Q and m represent the latent heat of vaporization, the specific heat of the water, the heat transfer rate and the mass flow rate of the water, respectively. The subscripts 1, 2 and 3 stand for the heat absorbed by dry stone matter, water heated to the desired temperature and water evaporation heat, respectively. Assume that $Q_1 = (Q_2 + Q_3) \times 0.5$.

2.3.2. The calculation formula of humid air.

Humid air can be regarded as the ideal gas mixture when it is at atmospheric pressure [5].

$$d = 0.622 \times \frac{\varphi \times P_s}{P - \varphi \times P_s}$$

(4)

$$h = 1.005t + d \times (2501 + 1.86t) \quad (5)$$

where d is the moisture content, ϕ is the relative humidity, P_s is the saturated vapor pressure, h is the enthalpy and t is the temperature.

2.3.3. The heat pump system.

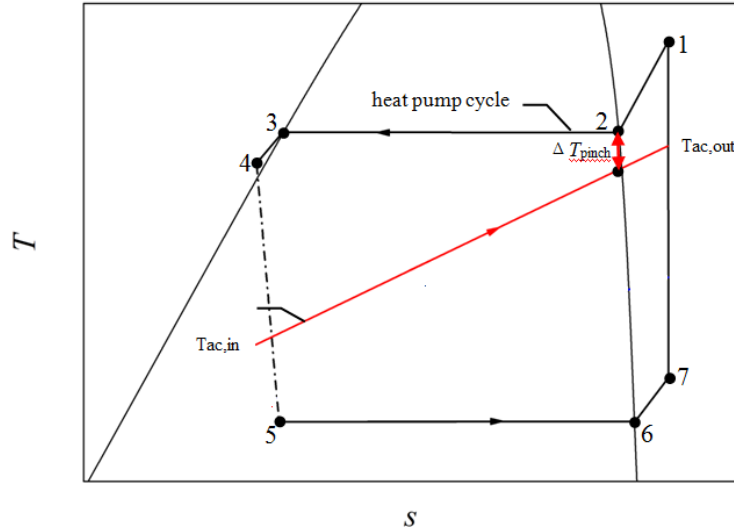


Figure 2. T-S diagram of heat pump cycle[6].

T-s diagram of heat pump cycle is shown in figure 2. The low-pressure sub-cooled steam point 7 is compressed to point 1, which is an adiabatic compression. It becomes saturated liquid point 3 after release heat at the same pressure, and sub-cooled to point 4. The refrigerant absorbs heat to point 7 after it is expanded from point 4 to point 5. The theoretical cycle shall be deemed reversible process except the constant-enthalpy process; it is possible to calculate by the equilibrium state parameters of the refrigerant. The heat balance equation of fresh air and refrigerant in condenser is as in equation (6).

$$Q_c = m_f(h_1 - h_4) = m_a(h_{ac,in} - h_{ac,out}) \quad (6)$$

Where $h_{ac,in}$ and $h_{ac,out}$ are the enthalpy of the fresh air at the inlet and outlet of the condenser, m_f is the mass flow rate of the refrigerant of heat pump, m_a is the mass flow rate of the fresh air, h is the enthalpy of refrigerant.

The heat balance equations in evaporators are as follows.

$$Q_e = m_f(h_7 - h_5) = m_f(h_7 - h_4) = Q_{ww} + Q_a \quad (7)$$

$$Q_{ww} = m_{ww} C_{ww} \Delta T = m_{ww} C_{ww} (T_{ww,in} - T_{ww,out}) \quad (8)$$

$$Q_a = m_a (h_{ac,in} - h_{ac,out}) \quad (9)$$

Where the subscripts “ww”, “a”, “ww,in”, “ww,out”, “ae,in” and “ae,out” stand for the wastewater, air, the inlet side of the wastewater, the outlet side of the wastewater, the inlet side of the air in the evaporator and the outlet side of the air in the evaporator, respectively.

The pinch point temperature difference (PPTD) of condenser represents the narrowest point between the fresh air temperature curve and refrigerant temperature curve as shown in Figure 2. It generally occurs at the beginning of the condensation process and can be expressed as follows:

$$\Delta T_{pinch} = T_2 - T_P \quad (10)$$

Where T_2 is the condensing temperature; T_P represents the temperature of fresh air at the outlet of the condensing section in condenser.

The PPTD ΔT_{pinch} is 15°C, For condensing temperature T_2 , it is given an assumed value first, then all the state points of the cycle can be simulated, after that T_P of the fresh air is determined according the follows:

$$T_P = T_{ac,out} - \frac{h_1 - h_2}{h_1 - h_4} (T_{ac,out} - T_{ac,in}) \quad (11)$$

If the difference of T_P and T_2 is not equal to $\Delta T_{pinc h}$, the value of T_2 is adjusted and iterated to meet the PPTD $\Delta T_{pinc h}$.

Assuming that part of the refrigerant m_{f1} in the air-source evaporator is heated to the saturated steam, and the rest of the refrigerant m_{f2} is overheated to superheated steam in the water-source evaporator.

$$m_f = m_{f1} + m_{f2} \quad (12)$$

$$m_{f1}(h_6 - h_4) = Q_a \quad (13)$$

The theoretical compression work shows as:

$$W = m_f(h_1 - h_7) \quad (14)$$

The heat of the fresh air get can be calculated as following.

$$Q = Q_e + W = m_a(h_{ac,in} - h_{ac,out}) \quad (15)$$

2.4. The performance evaluation indices

Heat pump dryers have a lot of performance indicators. Commonly used to evaluate the performance of the heat pump drying device are the specific power consumption and the thermodynamic coefficient of the heat pump.

The COP of the overall system can be defined as in equation (16).

$$COP = \frac{h_7 - h_4}{h_1 - h_7} \quad (16)$$

Dry evaporate 1kg of water consumed energy in the process of known as the unit energy consumption of SPC [7]. The energy dissipations of the 1kg of water evaporation in the drying process are called the unit energy consumption of SPC, which reflects the relationship between the dehumidification and energy consumption. This SPC will be defined in equation (17).

$$SPC = \frac{Q}{COP} \quad (17)$$

2.5. The Feasibility Evidences

Under the assumptions of the operating system, the basic parameters as follows:

1. The pressure losses of refrigerant in condenser and evaporator are ignored.
2. For the heat pump cycle, R123 is employed as the working fluid. The evaporator outlet superheat degree is 5°C to ensure the operation security of the compressor. The condenser outlet subcooling degree is 5°C . The PPTD $\Delta T_{pinc h}$ is 15°C . It is assumed that h_4 equals h_5 .
3. Setup parameter : The inlet temperature of new air is 25°C , the relative humidity of fresh air is 0.5, the aimed temperature of drying air is $T_{ar,in} = 70^\circ\text{C}$, the inlet temperature of evaporator is $T_{ae,in} = 70^\circ\text{C}$.
4. The circulating water temperature is $T_{ww,in} = 25^\circ\text{C}$ after stone polished and cut, with an outlet temperature $T_{ww,out} = 20^\circ\text{C}$ away from water-source evaporator.

Theoretical cycle analysis is based on the thermodynamic properties to evaluate the cycle performance of working fluid, the results list in table 2.

Table 2. The R123 parameter values of heat pump drying system at various points.

Each state point	Temperature T (°C)	Pressure P (MPa)	Enthalpy h (kJ/kg)	Entropy s (kJ/kg·K)
1	-	0.4139	424.66	1.67
2	73.5	0.4139	-	-
3	73.5	0.4139	-	-
4	68.5	0.4139	270.81	-
5	-	-	270.81	-
6	20.0	0.0756	393.49	-
7	25.0	0.0756	396.93	1.67

As the moisture content of exhaust is higher, affecting the drying effect, the best option is discharge into the atmosphere directly. Hot air exchanges the heat with refrigerant in the evaporator after living the drying oven and then discharge into the atmosphere directly. The results of each state moist air list in the table 3.

Table 3. The parameter values of humid air in the heat pump drying system.

Each state point	Condenser		Drying Oven		Air-Source Evaporator	
	T _{ac,in}	T _{ac,out}	T _{ar,in}	T _{ar,out}	T _{ae,in}	T _{ae,out}
Temperature (°C)	25	70	70	40	40	30
Moisture content (kg)	0.0098	0.0098	0.0098	0.0181	0.0181	0.0181
Enthalpy (kJ/kg)	50.31	96.36	96.36	86.71	86.71	76.32

Because of the open type heat pump drying is influenced by the environment, the waste water recycling system as the auxiliary heating source. The reason is that Water has a higher specific heat and better heat transfer performance, temperature and flow stability. Temperature of wastewater is constant all over the year and its temperature is almost 20 higher than the ambient air temperature and the amount of it is significantly high and its flow rate is almost constant all over the year. For the sake of reaching the same drying efficiency, the calculation results of this system are as follows, it can be seen from the result that the value are in a reasonable range.

Table 4. The parameter values of the heat pump drying system.

Parameter	COP	Q (kJ/kgmin)	m _{ww} (kg/min)	SPC (kJ/kg)
Value	5.55	3756.69	159.99	676.88

3. Results and discussion

Since the huge of waste water quantity and heat excess supply of water source, the parameters passes through the refrigerant cycle system set to a fixed value.

3.1. Contrast with single air source heat pump

To highlight the advantages of the heat pump system that take stone processing plant's waste water as heat source, compared with traditional air source heat pump. Replacing the existing wastewater recycling system with air heat exchanger, the required quantity of heat m_2 is provided by air. The parameters of the air inlet temperature of the evaporator is $T_{ae2,in} = 20^\circ\text{C}$, relative humidity 0.5 and

outlet temperature of the evaporator is $T_{ae2,out} = 10^{\circ}\text{C}$. The comparison of both results shows in the table 5.

Table 5. The results contrast of the wastewater source heat pump and the air source heat pump.

	Parameter Value	m_{f2} for air source	m_{f2} for water source
Inlet	Temperature Of Evaporator ($^{\circ}\text{C}$)	20.00	20.00
	Relative Humidity	0.50	-
	Enthalpy (kJ/kg)	38.54	-
Outlet	Temperature Of Evaporator ($^{\circ}\text{C}$)	10.00	15.00
	Relative Humidity	1.00	-
	Enthalpy (kJ/kg)	28.35	-
Volume	m_{a2} (kg)	311.96	151.81
	m_{a2} (m^3/min)	241.83	0.10

Based on the data in this table, a pure air source heat pump source volume is 2418 times as much as the source volume of the wastewater source heat pump system for making the same quantity of heat. Since the density of air is far less than the water, the volume of air heat exchanger is much larger than the water-cooled heat exchanger's, equipment cost and covering area increase. Instead, the heat tubes of waste water sources is embedded in the heat recovery pool, which needs small covering area and the waste heat recovery will be conducive to wastewater treatment. Reducing the temperature of the wastewater accelerate the velocity of sludge sedimentation to a certain extent. Silt suction machine are adopted regularly to remove the sludge at the bottom of the first settlement tank and second settlement tank. The fresh water supply is needed in order to maintain the water level.

3.2. Influence of different factors

Since the wide range of temperature in southern summer and winter especially in Fujian. Summer temperatures up to 30°C , and the winter temperature is not below 9°C . The influences of air temperature on the unit operation were considered. To illustrate the feasibility of the system under different air parameters, the temperature change range is set from 5 to 30°C .

Seven of alternative refrigerants (R152a, R123, R1234yf, R1234ze, R600a, R22 and R600) were invested in these case, with the fresh air temperature is set within $[5-30^{\circ}\text{C}]$, and the changes of the COP as shown at figure 3. When the refrigerant is R123, m_a changed as shown in figure 4. According to figure 4, the higher temperature of the fresh air, the moisture absorption of the air is stronger at the same relative humidity. In the case of the same amount of drying stone, summer need less air than winter and the higher temperature air has a higher COP value.

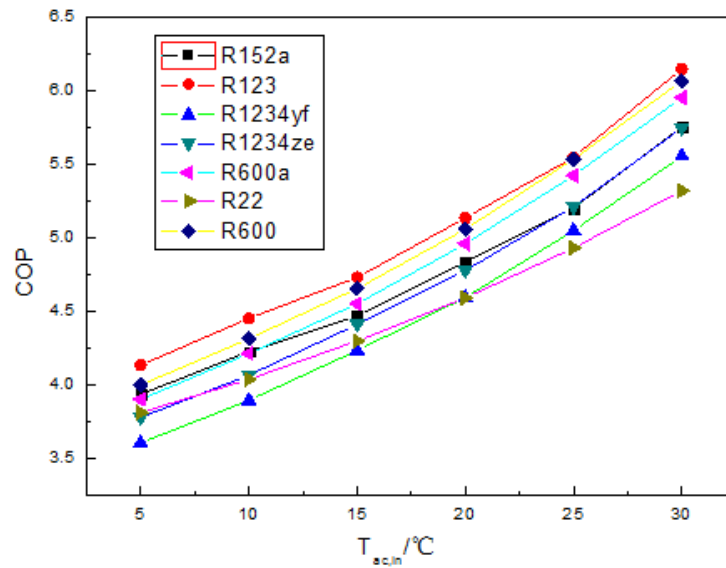


Figure 3. COP of different refrigerants.

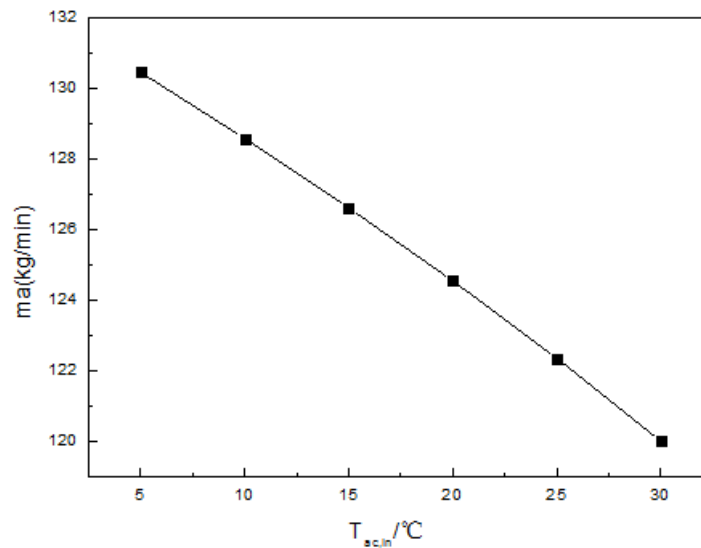


Figure 4. m_a of different refrigerants.

Table 6. All the properties of the refrigerants[8].

Refrigerator	Safety Level	Boiling Point (°C)	P_{cond} (MPa)	T_{cond} (°C)	ODP	GWP	COP
R152a	A2	-25.0	2.0599	74.0	0	0.02	5.75
R123	B1	27.7	0.4193	74.0	0.012	120.00	6.15
R1234yf	A2	-29.4	2.0753	70.7	0	4.00	5.55
R1234ze	A1	-30.0	1.6852	72.0	0	6.00	5.75
R600a	A3	-11.8	1.1429	72.3	0	0.10	5.95
R22	A1	-40.8	3.2911	74.6	0.034	1700.00	5.32
R600	A3	-0.5	0.8624	72.8	0	20.00	6.06

All the “Properties” of the refrigerants, including: Safety level, boiling point, T_{cond} , P_{cond} , ODP and COP, were included in the table.6. Combining with the above three figures, it can be seen from that the change of environmental temperature has great influence on operation of device. The temperature difference is decrease with the increase of environmental temperature, so the value of COP increased. R123 has the highest efficiency with the maximum value of COP at the different working conditions. R22 is normally used in the heat pump as a work fluid. While both R123 (ODP=0.012) and R22 (ODP=0.034) have a value of ODP, which will be limit usage by Montreal Protocol [9]. Although, R152a, R600a and R600 have ODP=0, and with lower GWP [10,11], they are highly flammable. R152a must be equipped with the independent secondary loop device making an additional cost. R1234yf and R1234ze was proposed as environmentally friendly refrigerants in recent years [12, 13], for their zero ODP and lower GWP and mild flammable, while have the lowest value of COP in this work. Comprehensive environmental benefits and the value of COP, the system select the refrigerant R123, which has high heating efficiency and environment friendly under a negative pressure working condition.

4. Conclusions

The heat pump system was studied in this paper, which provides necessary energy for the stone drying by recovery heat from the circulating water working in the processes of cutting and polishing. The energy of the circulating water is supplemented by the thermal energy produced during cutting and polishing. The wastewater is discharged from the stone processing work as stable heat source; the recovery technology for exhausting steam realize reliable operation; with obvious energy-saving effect, a small part of the power consumption can complete drying process; the proposed system is energy-saving and eco-friendly with reducing primary energy consumption and improving energy efficiency.

Compared with conventional air cooling systems, the required heat exchanger has many advantages such as: smaller size, more compact structure, lower investment cost, larger temperature range and so on. The R123 shows the superior thermal performance with the highest COP in the selected seven promising refrigerants. Therefore, this paper recommends R123 as the working refrigerant. The circulating water system is particularly suitable for the areas where water resources are scarce and the annual average temperature are over 10 °C, which provides a reference for practical engineering application.

References

- [1] Guo J 2013 *Research on optimization and operation strategy of air source heat pump water heater* (Shanghai: Shanghai Jiao Tong University)
- [2] Hepbasli A, Biyik E and Ekren O 2014 A key review of wastewater source heat pump (WWSHP) systems *Energy Conversion and Management* **88** 700-22
- [3] Shen C, Jiang Y and Yao Y 2012 A field study of a wastewater source heat pump for domestic hot water heating *J Build Services Eng Res Technol* **34** 433-48
- [4] Hu P and Zhu W B 2015 Performance analysis of Heat Pump Water Heating System with Cascade Utilization of Waste Heat from Wastewater *Proc. the 24th iir international congress of refrigeration* ed Chen Z S (Japan: Youkohoma)
- [5] Guo X 2012 *Design and research on an air low temperature drying cycle system* (Nanjing: university of Aeronautics and astronautics)
- [6] Lemmon E W, Huber M L and McLinden M O 2010 *Reference Fluid Thermodynamic and Transport Properties-REFPROP. 9.0.* (Gaithersburg: NIST Standard Reference Database 23)
- [7] Pan Y K 1998 *Modern drying technology* (Beijing: chemical Industry Press) p 12
- [8] Calm J M and Hourahan G C 2011 *Physical, safety and environmental data for current and alternative refrigerants* (Prague: Czech Republic) P 915
- [9] Li M 2014 *Comparative study on heat pump technology applied in waste heat recovery* (Tianjin: Tianjin University)

- [10] Garimella S 2003 Innovations in energy efficient and environmentally friendly space-conditioning systems *Energy* **28** 1593-614
- [11] McCulloch A 1999 CFC and Halon replacements in the environment *J. Fluorine Chemistry* **100** 163-73
- [12] Akasaka R, Tanaka K and Higashi Y 2010 Thermodynamic property modeling for 2,3,3,3-tetrafluoropropene (HFO-1234yf) *International Journal of Refrigeration* **33** 52-60
- [13] Brown J S, Zilio C and Cavallini A 2009 The fluorinated olefin R-1234ze(Z) as a high-temperature heat pumping refrigerant *International Journal of Refrigeration* **32** 1412-22