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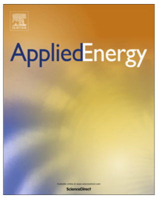

A comprehensive review on advances and applications of industrial heat pumps based on the practices in China

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HIGHLIGHTS

- Comprehensively reviewing industrial heat pump systems in China for the first time.
- Research and application advances in industrial heat pumps in China are discussed.
- Three typical examples of using industrial heat pumps are discussed in details.
- It identifies the further research needs on industrial heat pump in China.

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ABSTRACT

An industrial heat pump can upgrade heat from a low temperature level to a high temperature level with the aid of an external energy source. It has received considerable attention as an efficient means of waste energy recovery in the recent years in China. This paper summarizes the research work done and advances in the application of industrial heat pump systems in China, including advances in refrigerants, multistage system, double-effect absorption system, compression–absorption system, solar assisted system, and chemical heat pump system. Industrial heat pumps used in three industrial fields (drying of wastewater sludge, crude oil heating in oil field, and process heating in printing and dyeing) are discussed in detail. Three basic problems in designing an engineering heat pump system, i.e., selection of the type of heat pump and determination of its capacity, energetic and exergetic analyses of the heat pump, and estimation of investment payback time are discussed in the above three industries, respectively. Further research needs in China on industrial heat pumps are proposed, which may also be beneficial to the international community.

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Nomenclature

COP	coefficient of performance
P	input energy
Q	useful heat/heat transfer rate (kW)
W	work (kW)
T	temperature (°C)
m	mass flow (kg/s)
x	concentration of LiBr solution (%)
h	enthalpy (kJ/kg)
s	entropy (kJ/(kg K))
e	exergy (kJ/kg)
η	efficiency (%)

Subscripts

0	dead state
1, 2, 3...	state points in Fig. 25
A	absorber
G	generator
E	evaporator
C	condenser
SHX	solution heat exchanger
s	strong solution
w	weak solution
r	refrigerant
i	inlet stream
o	outlet stream

1. Introduction

With the increase in global energy consumption, energy issues and environmental problems are becoming increasingly prominent. At present, fossil fuels are the main sources of energy, and their depletion is a major challenge for humanity. In the year 2012, the global consumption of coal, which is increasing at the highest speed among all fossil fuels, increased by 2.5%; meanwhile, coal consumption in China contributed to more than half of the world's total consumption for the first time [1]. The consumption of large amounts of fossil fuels leads to a severe problem of environmental pollution, and China is now a large contributor to the greenhouse gas emissions. Faced with the problems of gradual exhaustion of fossil fuels and pollution of the environment, researchers are making efforts in two areas: developing new energy sources, especially renewable energy sources such as solar energy, wind energy, and tidal energy; and improving energy efficiency to reduce the consumption of fossil fuels and the pollution caused by their usage.

Process industries are some of the major consumers of energy; in China, they are the predominant consumers. The statistics of energy consumption in China during the year 2010 are shown in Fig. 1. It can be seen that the primary energy consumption of industry takes 71.1% of the total national energy consumption [2]. At present, the efficiency of energy utilization by the industries in China is lower than the world averaged, and more than half of the energy consumed in process industries is turned into the waste heat in the form of exhaust gases and waste water. It is estimated that only 30% of the waste heat is reused in China [3], which is one of the reasons for the low efficiency of energy utilization. The industrial high-grade waste heat can be reused for power generation. The large amount of low-grade waste heat, with low and moderate temperatures (up to a maximum of 100 °C), can be utilized with the help of a heat pump. Industrial heat pumps can recover the waste heat from industrial processes and transfer the heat from the low temperature medium to a high temperature medium with an aid of an external energy source. The high-

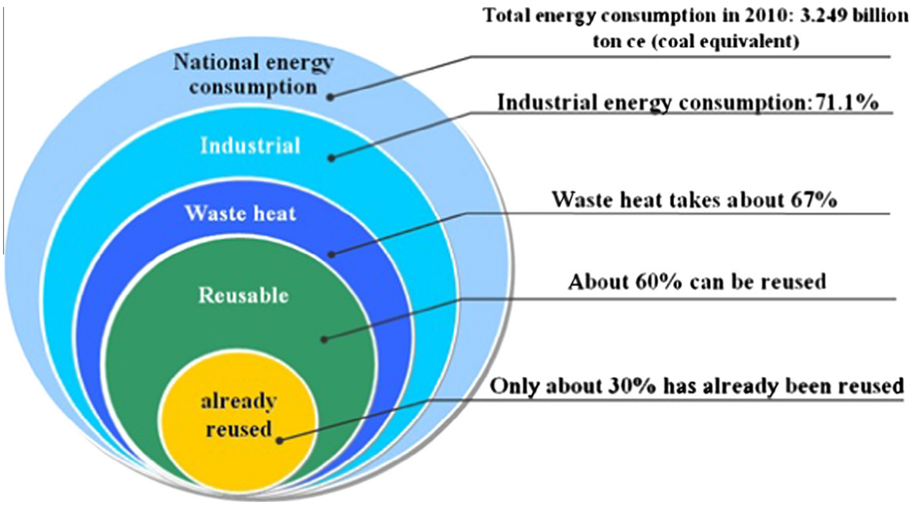


Fig. 1. An estimation of waste industrial heat in China [2].

grade heat yield obtained using industrial heat pumps can be applied in many industrial processes.

Although Canren Lv of Tianjin University, the pioneer of heat pump study in China, had suggested the need for application of heat pumps in 1955 [4], only in the recent two decades, studies have been conducted on heat pumps for residential usage for energy saving. To date, heat pump techniques for residential usage have been well developed to meet the heating requirements of a section of the residents in China [5,6]. However, heat pumps have not been widely applied for industrial usage for recovering low-grade waste heat in China [7]. The International Energy Agency (IEA) launched a new project named "Application of Industrial Heat Pumps" in 2010, which focuses on heat pumps for high-temperature industrial and commercial applications [8]. In recent years, the Chinese government has been executing a policy of saving energy and reducing greenhouse gas emissions, and significant progress has been made on the use of the industrial heat pump technique to recover industrial waste heat in China [9–12]. Although many studies focused on theoretical aspects and experiments on heat pumps in laboratories, there still exist some problems related to technology, design, and implementation of industrial heat pumps. Therefore, a comprehensive investigation on system research and various applications of industrial heat pumps is needed to promote the development of industrial heat pump technology in China. Extensive application of industrial heat pumps in China will reduce greenhouse gas emissions and contribute to low-carbon environment, which is beneficial to humanity. Further, the lessons and experience related to successful cases of industrial heat pumps can be shared with the other developed regions of the world. Thus, the objective of the present paper is to present a comprehensive review on the advances in industrial heat pumps and their applications during the last two decades in China, and to propose the research needs and development direction in the near future. The outline of the paper is shown in Fig. 2. In the following sections, the focus will be on the work published by the Chinese authors known to the present authors; in addition, some important international studies will also be covered. It should be noted that management and operational control are important aspects in the application of industrial heat pumps. However, the present paper focuses only on the problems related to thermo-fluid science and engineering.

2. Types of industrial heat pumps

There are several heat pump cycles in industrial applications. These cycles can be divided into the following categories: vapor compression cycle (mechanical compression cycle), mechanical vapor recompression cycle, thermal vapor recompression cycle, absorption cycle, and chemical heat pumps. The steady-state performance of a heat pump cycle is evaluated by a coefficient called the coefficient of performance (COP). The COP is defined as

$$COP = Q/P \tag{1}$$

where Q is the useful heat delivered and P is the high-grade (primary) energy input.

The basic principles of the different types of industrial heat pumps are briefly introduced below.

The vapor compression cycle usually consists of a compressor, an expansion valve, and two heat exchangers, referred to as the evaporator and the condenser. These devices form a closed circuit, and the refrigerant circulates through the entire cycle. The schematic of this cycle and its corresponding p–h (pressure–enthalpy) diagram are shown in Fig. 3. In the evaporator, the liquid refrigerant evaporates by absorbing heat (state point 1), and then the superheated vapor flows through the compressor (state point 2) and enters the condenser, where the hot vapor condenses and the condensation heat is given off to the cooling water, air, or other energy users (state point 3). The liquid refrigerant then passes through the expansion valve (state point 4) and returns to the evaporator, and thus completes a full cycle. During the process, the thermal energy at the evaporation temperature is upgraded

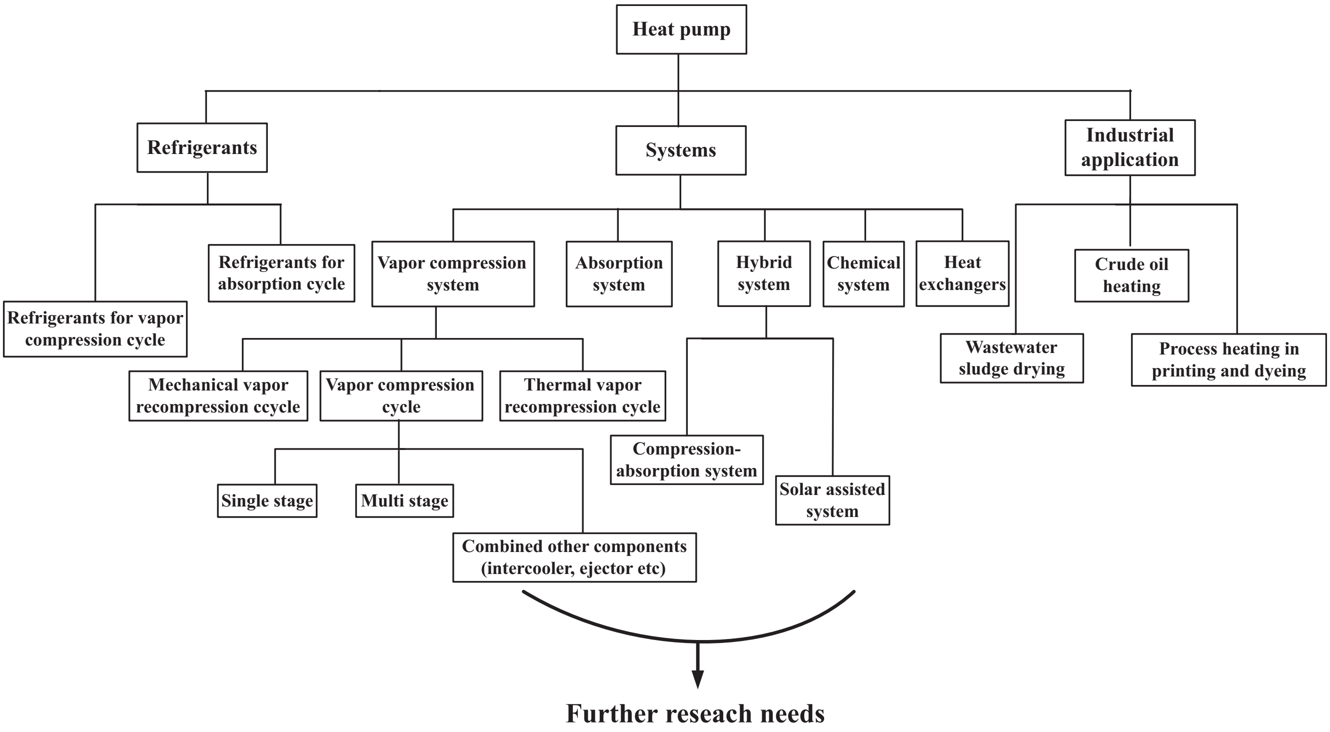
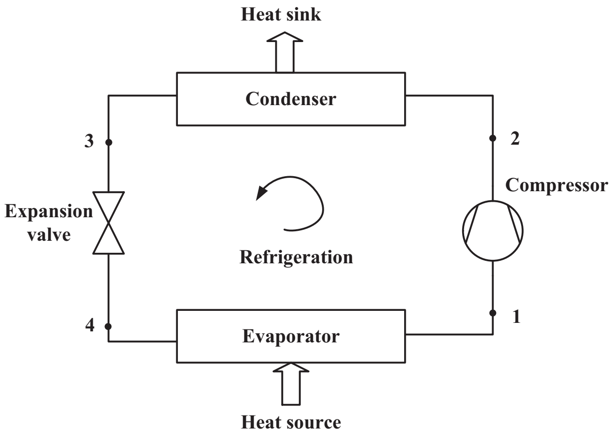
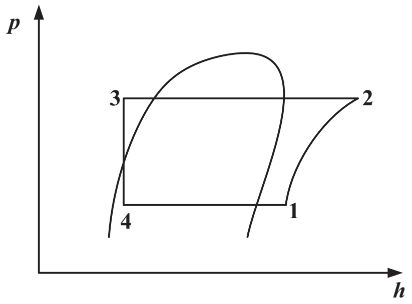


Fig. 2. The outline of the paper.



(a) Schematic diagram



(b) Pressure-enthalpy diagram for thermodynamic cycle

Fig. 3. Vapor compression heat pump system.

to the condensation temperature, and this higher temperature can be used for various industrial heating purposes.

The mechanical vapor recompression (MVR) cycle has several possible system configurations. The most common one is the semi-open type (Fig. 4), in which the vapor used as the heat source is compressed by a compressor, and then the vapor condenses in the condenser and gives off heat to the heat sink.

The thermal vapor recompression cycle (TVR) is shown in Fig. 5. Working steam at high temperature and high pressure flows through the nozzle of the ejector; meanwhile, the refrigerant in the evaporator evaporates and enters the nozzle as the second steam. The two parts get mixed, and then the mixed steam condenses in the condenser and releases heat to the user. The thermal vapor recompression cycle is driven by heat, and not by mechanical energy; in this respect, it is different from other two types described above.

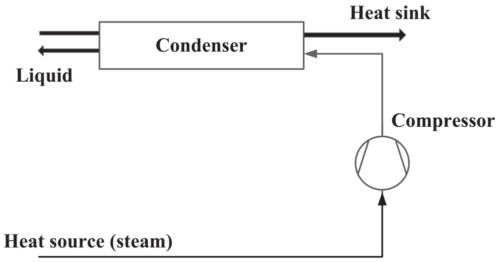


Fig. 4. A mechanical vapor recompression heat pump system.

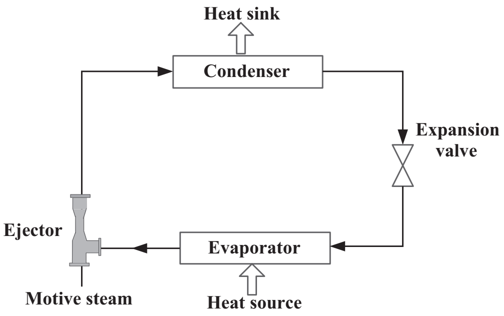


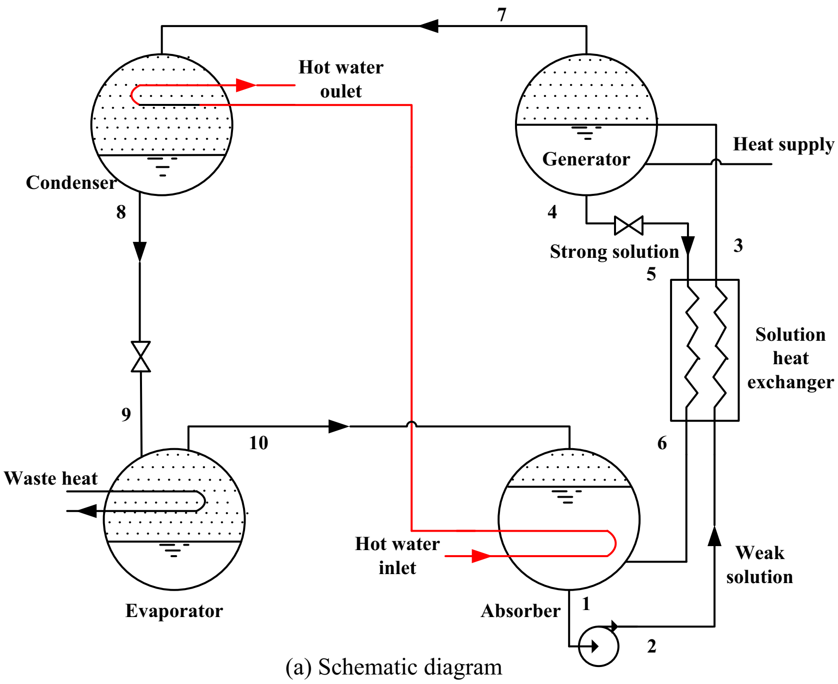
Fig. 5. A thermal vapor recompression heat pump system.

There are two configurations of the absorption cycle: absorption heat pump (type I) and heat transformer (type II). The basic components of both the types are the generator, absorber, condenser, evaporator, and solution heat exchanger. In type I, the waste heat, which is at a low temperature level, is upgraded to a medium temperature level by consuming heat at a high temperature level. Fig. 6 illustrates the schematic of type I absorption heat pump and the *p*–*t* (pressure–temperature) diagram of its corresponding thermodynamic cycle. The heat pump cycle is composed of a refrigerant circuit and an absorbent circuit. Normally, the working medium pair used is LiBr/H_2O. The working process of the refrigerant (water) is as follows: The LiBr solution in the generator is heated to produce high temperature and high-pressure vapor; the vapor enters the condenser, where it condenses and gives off condensation heat; the vapor expands in the expansion valve and enters the evaporator, where it absorbs the waste heat and evaporates. The working process of the absorbent (LiBr solution) is as follows: The strong solution from the generator enters the absorber, where the vapor is absorbed and gives off heat; the diluted solution is pumped into the solution heat exchanger, where it transfers heat to the strong solution from the generator; the heated solution (diluted solution) enters the generator, where the vapor is boiled off, and then the vapor condenses in the condenser. During the process, heat is released by the absorber and the condenser successively. In the *p*–*t* diagram, process path 1-3-4-6 indicates the circulation path of the LiBr solution. Generally, the COP of type I absorption heat pump is in the range of 1.3–1.4 when the boiler efficiency is considered.

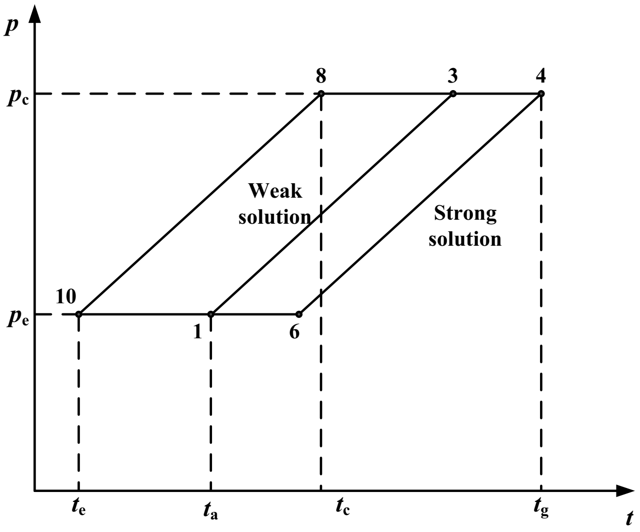
Fig. 7 shows the schematic and *p*–*t* diagram for type II absorption heat pump. In the *p*–*t* diagram, cycle process path 1-3-4-6 indicates the solution process. In this cycle, heat is supplied at a medium temperature level, and a part of it is upgraded to a high temperature level, while the other part is discharged at a low temperature level; this differs from the cycle of type I absorption heat pump. In type II absorption cycle, hot water is heated by the absorber and transported to the user. The COP of type II absorption heat pump is approximately 0.5, which means half of the heat at the medium temperature level is upgraded to a high temperature level.

The temperature levels of the heat supplied by these two types are different, which is due to the difference in the pressure levels in the four main components (generator, absorber, condenser, and evaporator) in the two cycles. The temperature in type I absorption heat pump may reach 100 °C, while that in type II pump reaches approximately 150 °C.

The final category is the chemical heat pump. The chemical heat pump absorbs low temperature heat by endothermic reaction and releases thermal energy by exothermic reaction, and the quality of the thermal energy stored by the chemical substances is upgraded to a higher level based on the reversible chemical reaction. The chemical heat pump can not only improve the quality of thermal energy, but also realize higher thermal energy storage. The advantages of high energy storage capacity, long term storage of chemical substances, and low heat losses suggest that the chemical heat pump can be a choice for upgrading the low-grade heat as well as for storing energy.



(a) Schematic diagram



(b) Pressure-temperature diagram

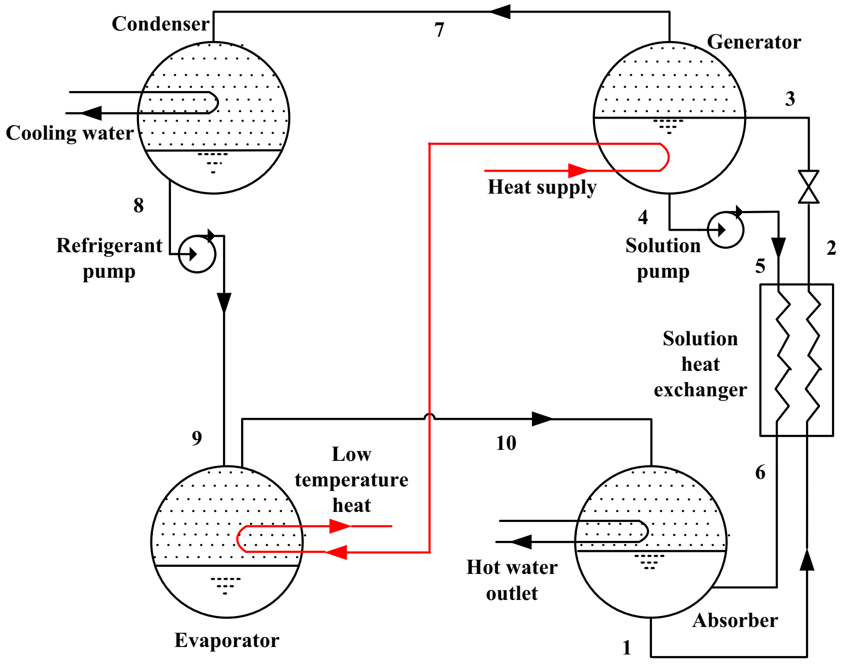
Fig. 6. Type I absorption heat pump system.

The chemical reaction occurring in a chemical heat pump reactor can be of the form: $A + B \rightleftarrows C$.

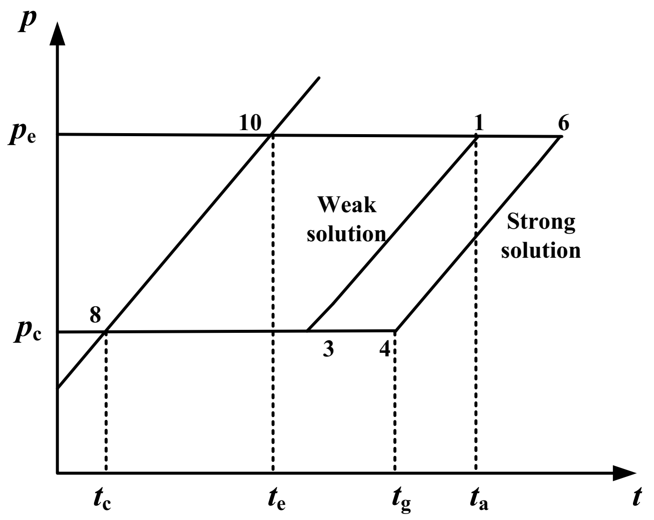
Here, the forward and backward reactions take place at two different temperature levels, thus resulting in upgradation of the low temperature heat to higher temperature heat. Fig. 8 shows a simple chemical heat pump system with a reversible reaction. During the backward reaction ($C \rightarrow A + B$), heat is supplied to the endothermic reactor from a low-temperature heat source, while in the forward exothermic reaction ($A + B \rightarrow C$), heat is released by the exothermic reactor at a higher temperature.

There are various chemical substances that can be used in a chemical heat pump. Chemical heat pumps can be classified as organic and inorganic pumps according to the working substance; they can also be divided into two types, solid–gas and liquid–gas, based on the phase of the working substance [13].

In China, space heating and cooling accounts for 65% of the energy consumption in the building sector [14], and the energy is primarily provided by natural gas or electricity. Heat pump as an efficient and green technology has the potential to provide hot water for domestic use for residents, and reduce fossil fuel consumption in building operations. With the encouragement and support from the government and relevant departments, residential heat pumps have developed rapidly in China, and have entered a booming period, and their applications have been widespread [15]. While the industrial heat pumps normally employ industrial waste heat as the heat source, the heat source for residential heat pumps can be air, soil, waste heat, or surface and ground water. Thus, the residential heat pump systems can be divided into the following categories: air source heat pump system (ASHP), ground source heat pump system (GSHP), waste water source heat pump system (WWSHP), and hybrid heat pump system. Depending on the type of heat source, the GSHP can be classified into three types: groundwater heat pump system (GWHP), ground coupled heat pump system (GCHP), and surface water heat pump system



(a) Schematic diagram



(b) Pressure-temperature diagram

Fig. 7. Type II absorption heat pump system.

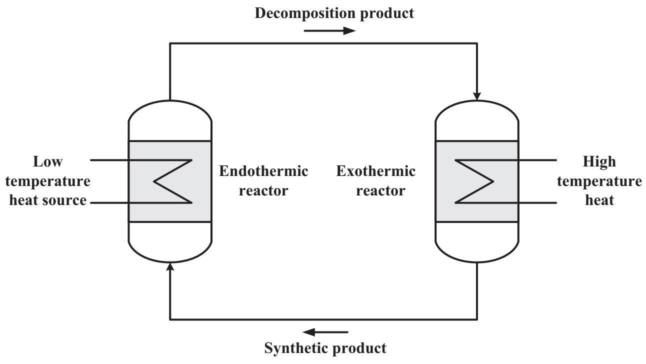


Fig. 8. A simple chemical heat pump system.

(SWHP) [16]. The advantages and limitations of each residential heat pump system are presented in Table 1.

Besides being used for air conditioning in buildings, residential heat pumps can also supply hot water (approximately 40–60 °C) for domestic usage. In contrast with the domestic heating by residential heat pumps, industrial heat pumps are used for process heating in various industries. Normally, the temperature demand in the industrial heating processes is high (above 75 °C), and some industries like the chemical industry need higher heating temperature (above 100 °C). Hence, the selection of suitable refrigerants and matched components for high-temperature heat pumps is a big challenge. Apart from the problem mentioned above, the initial investment of industrial heat pumps is high, and the payback time is a bit long. Both industrial and residential heat pumps involve technologies for energy saving and environment protection, and hence their application can bring both economic and environmen-

Table 1
Summary of the different types of residential heat pump systems.

	ASHP	GSHP	WWSHP	Hybrid heat pump
Heat source	Air	Soil, ground water, surface water	Sewage	Solar energy
Advantages	– Safe – Easy to maintain	– No influence by the climate – Safe – Easy to maintain	– The amount and temperature remains almost stable – The temperature in winter is higher than other heat source – Low cost – More effective than ASHP [17]	– Balance the temperature of ground and air – Higher energy saving rate – Flexible operation
Limitation	– Evaporator frosting problem – Not suitable for cold regions	– Geological condition – High initial investment – Disturb the soil temperature balance – Pollute the groundwater	– Corrosion and blockage in the heat exchanger	– High initial investment – Complicated system' – Higher requirement for installation and operation

Table 2
Comparison between the industrial heat pump and residential heat pump.

	Residential heat pump		Industrial heat pump	
Heat source	Air, soil, surface and ground water, waste water, solar energy		Waste heat, solar energy	
Types	ASHP; GSHP; WWSHP; Hybrid heat pump		Vapor compression heat pump (open and closed cycle); Absorption heat pump; Chemical heat pump; Hybrid heat pump	
Application	Heating and cooling for buildings; Domestic hot water; 40–60 °C		Industrial process heating; >75 °C	
Limitation	Based on the climate and region		Based on the temperature and continuity of waste heat	
COP	GWHP [14]	$COP_{cooling} = 3.29$ $COP_{heating} = 2.79$	Vapor compression heat pump [25]	$COP = 3.9$
	GCHP [18]	$COP_{cooling} = 3–3.88$ $COP_{heating} = 2.55–3.25$	Vapor compression heat pump [26]	$COP_{average} = 4.2$
	Solar + ASHP + WSHP [19]	$COP_{heating,average} = 3.7$	Vapor compression heat pump [27]	$COP = 5.207$
	Solar-GCHP [20]	$COP_{heating,hp} = 4.28–4.36$ $COP_{heating,system} = 7.88–8.17$	Absorption heat pump (Type I) [25]	$COP = 1.56$
	Solar-GCHP [21]	$COP_{heating,system} = 4.8$ $COP_{heating,hp} = 5.77–7.95$	Absorption heat pump (Type II) [28]	$COP_{average} = 0.47$
	Solar-GSHP [22]	$COP_{heating,system} = 3.17–3.42$ $COP_{heating,hp} = 4.8–5.4$	Solar assisted heat pump [29]	$COP = 5.369$
Technical problem	– R&D and operation technique – Installation – Heating/cooling load imbalance		– High temperature refrigerants and matched components – High initial investment and long payback period – Exploit efficient system	
Economic benefits	– GWHP: saving 42.9% energy compared with originally heat/cooling system [14] – GSHP: total energy saving were 109,856 TJ for five years in Shengyang, China [23] – GSHP + GWWHP: saving 1.25 million RMB in 2008 Beijing Olympic projects [24]		– Vapor compression heat pump: saving 153,820 RMB/year [26] – Vapor compression heat pump: saving 3.40 million RMB/year [30] – Absorption heat pump (Type II): saving 3.48 million RMB/year [28]	
Environmental benefits	– GSHP: 3.4 million tons of CO_2 equivalents reduced for five years in Shengyang, China [23] – GSHP + GWWHP: reducing 3105 t of CO_2 in 2008 Beijing Olympic projects [24]		– Absorption heat pump (Type II): 2336.7 tons of fuel, and 2337 tons of exhaust gas reduced [28] – Vapor compression heat pump: reducing 4337.95 kg NO_x, 1535.87 kg of dust and 4982.78 kg of SO_2 [27]	

tal benefits. A systematic comparison of the industrial and residential heat pumps is presented in Table 2.

3. Refrigerants

In this section, the refrigerants for vapor compression heat pumps and absorption heat pumps will be described.

For the vapor compression cycle, the studies on the refrigerants focus on seeking alternatives to R22, R114, etc., and searching for a refrigerant with a high condensation temperature. Compared with the conventional vapor compression cycle heat pump, the heating temperature used in industrial heat pumps is quite high, normally above 75 °C; hence, one area of research emphasis on industrial heat pumps is to seek suitable high temperature refrigerants. Two types of refrigerants are discussed here: (i) natural refrigerants like CO_2, NH_3, and hydrocarbon; (ii) artificial refrigerants such as HCFC, HFC, and their mixtures. The requirements of the refrigerants are, high critical temperature, low pressure range, no ozone depletion potential (ODP), low global warming potential (GWP), nonflammability, and being non-toxic. However, to date, researchers have not found an ideal refrigerant that can satisfy all the above requirements. However, because of the efforts of worldwide researchers, some refrigerants can meet the requirements to a certain degree.

R22 had been widely used in the air conditioning and heat pump applications; however, it has been gradually replaced because of its significant greenhouse effect. Recently, researchers in China and abroad have focused on seeking new refrigerants and testing their performance. The possibility of replacing R22 with R134a and R22/R134a was discussed by Karagoz et al. [31], and they found that by using R134a and R22/R134a with an appropriate mixture ratio, a higher COP can be obtained compared to R22. Further, the COP can be improved by approximately 25% when the mass percentage of R134a is 50% of the mixture R22/R134. Lee et al. [32] found that R32/R152a mixture can be a substitute for R22. Park et al. [33–35] measured the thermodynamic performance of R431A, R432A, R433A, and R22 under the same conditions, and demonstrated that both R432A and R433A are good alternatives to R22. Park and Jung [36] found that R170/R290 mixture is also an excellent alternative to R22. Chang et al. [37] experimentally investigated the performance of hydrocarbon refrigerants, including propane (R290), isobutane (R600a), butane (R600), propylene (R1270), mixtures of propane/isobutane (R290/600a), and propane/butane (R290/600). The results showed that the COPs of R1270, R290/600a, and R290/600 are higher than the COP of R22. Longo et al. [38] presented a low GWP refrigerant R1234ze(Z), and tested the heat transfer coefficient and pressure drop during the condensation of R1234ze(Z) vapor in a heat exchanger. They compared the results with those of R236fa, R134a, R600a, and R1234ze(E), and found that R1234ze(Z) has the highest heat transfer coefficient. Therefore, they concluded that R1234ze(Z) is a promising refrigerant for high-temperature heat pumps. Brown et al. [39] also found that R1234ze(Z) is a possible alternative to R114 as a refrigerant for high-temperature heat pumps. Fukuda et al. [40] performed thermodynamic assessment of R1234ze(E) and R1234ze(Z), and concluded that R1234ze(Z) is suitable for high-temperature heat pump systems in industrial applications. Sarkar and Bhattacharyya [41] conducted performance evaluations on R744/R600 and R744/R600a and observed that R744/R600a has a better performance at a condenser outlet temperature of 73 °C, while the trend is reversed at 100 °C, owing to the fact that R744/R600 possesses a higher temperature glide. They also compared the performances of R744/R600 and R744/R600a with those of pure refrigerants (R114, R600a, R744, and R600), and found that refrigerants mixtures R744/R600 and R744/R600a, and refrigerant R744 show superior performance than R114, but R744 has an excessive high-side pressure. Therefore, the refrigerant mixtures R744/R600 and R744/R600a provide an alternative to R114 for high temperature applications. Chamoun et al. [42] studied the performance of a heat pump using water as the refrigerant; they demonstrated that the heat pump can recover waste heat, and that a temperature of 90 °C can be attained.

Chinese researchers in various universities have also been very active in searching for alternatives. The research group led by Zhu and Shi [43] in Tsinghua University developed a ternary mixture of R124/R142b/R600a named HTR01 that can be used for moderately high-temperature heat pumps. They tested the performance of a heat pump using HTR01 as the refrigerant, and the major results indicated that the temperature of the outlet water from the condenser can reach 90 °C, with a COP above 3. As an extension of this work, they subsequently developed refrigerant mixtures HTR02, HTR03, and HTR04, and tested their thermal performances through experiments. When an R134a compressor was filled with HTR03 and HTR04, the heat pump could stably produce hot water with temperature above 85 °C. Heat pumps employing HTR01 and HTR02 are already being produced and utilized in various industrial processes in China [44].

The researchers in Tianjin University are also very active in developing new refrigerants for refrigeration and industrial heat pumps. Pan et al. [45] of Tianjin University selected several refrigerants for a moderately high-temperature heat pump. They tested the performance of a water-to-water vapor compression heat pump system that uses R245fa, R600, R600a, and a zeotropic refrigerant mixture R600/R245fa (mass fraction: 2.83%/97.17%). The experimental results showed that both R600 and R600a offer good cycle performance in a moderately high-temperature heat pump cycle. The cycle performance of R600 is better than that of R600a under higher temperature conditions, and the COPs of R600 and R600a are 3.84 and 3.33, respectively, when the evaporating temperature is 40 °C and the condensing temperature is 90 °C. Besides, the zeotropic refrigerant mixture R600/ R245fa offers a better performance than R245fa [46]. Zhang et al. [47] in Tianjin University proposed three non-azeotropic refrigerant mixtures named M1A (having mass fraction of 20% R152a and 80% R245fa), M1B (having mass fraction of 37% R152a and 63% R245fa), and M1C (having mass fraction of 50% R152a and 50% R245fa), and conducted experiments in the condensing temperature range of 70–90 °C. All the three mixtures have higher COPs and higher capacities when compared with R245fa, with M1B being the best one. They considered that it is the most suitable refrigerant for a moderate/high-temperature heat pump. Another new near-azeotropic refrigerant mixture named BY-4 was presented by Yu et al. [48] because of its good comprehensive property and excellent cycle performance.

In the Compressor Institute of Xi'an Jiaotong University, studies have been conducted on transcritical CO_2 heat pumps, and the researchers of this Institute developed a CO_2 heat pump water heater that can supply hot water at 90 °C, by working in cooperation with Suzhou Halddane energy corporation [49]. Yu et al. [50] of the same university studied the performance of a transcritical heat pump cycle employing an azeotropic refrigerant mixture R32/R290, and found that the heat pump cycle can produce hot water with temperatures up to 90 °C. Therefore, the azeotropic refrigerant mixture R32/R290 is recommended for high-temperature water heating applications.

As far as the Chinese corporations are concerned, Yantai Lande air conditioning industries corporation developed refrigerants Land01 and Land03. The heat pump systems employing Land01 and Land03 as refrigerants can provide hot water with temperatures

Table 3
Refrigerants for industrial vapor compression heat pumps.

Refrigerants	Maximum sink temperature (°C)	Critical temperature (°C)	Critical pressure (MPa)	ODP	GWP/100a	Toxicity	Flammability
NH_3[54]	110	132.5	11.35	0	0	Yes	Medium
CO_2[54]	130	31.1	7.38	0	1	No	No
R245fa[54]	140	154.0	3.65	0	950	Yes	No
R600a[54]	140	134.7	3.63	0	<1	No	High
DR-2[54]	160	171.3	2.903	0	9.4	No	No
SES36[54]	160				Low	Low	No
R134a[38]	<90	101.06	4.059	0	1300	Low	No
R1234ze(z)[38]	–	150.1	3.64	0	<10	No (expected)	Low (expected)
HTR01[43]	90	124.3	3.759	0.04	1500	No	No
HTR03[44]	85	111.42	3.8797	0	1300	No	No
R500/R245fa [45]	–	153.9	3.66	0	966	–	–
R123[45]	<100	183.68	3.662	0.02	77	Low	No
R142b[45]	<100	137.2	4.12	0.07	2310	Low	Low
BY-4[48]	110	150.2	4.44	0	755	–	–

above 85 °C, and hence the heat pump systems are suitable for recovering low-grade waste heat [51].

This section covers the refrigerants used in the absorption cycle. Chinese authors have also made some contributions in this regard. Sun et al. [52] proposed a new working fluid LiBr + $LiNO_3$ + H_2O, and simulated the thermodynamic properties of a single effect absorption heat pump employing the new refrigerant. Their results showed that the COP of LiBr + $LiNO_3$ + H_2O can be 5% more than that of LiBr + H_2O. Zhang et al. [53] simulated the performance of a single-stage absorption heat transformer employing 1-ethyl-3-methylimidazolium dimethylphosphate and water (H_2O + [EMIM] [DMP]), and the simulated results were compared with those of a system employing LiBr + H_2O and TFE + E181 (Trifluoroethanol (TFE)–tetraethylenglycol dimethylether (TEGDME or E181)). They found that both the COP and exergy efficiency of H_2O + [EMIM] [DMP] are higher than those of TFE + E181, but lower than those of LiBr + H_2O, and that H_2O + [EMIM] [DMP] is the most suitable working pair for industrial applications, because it causes lower corrosion of iron and steel materials.

As a short summary, the refrigerants that can be used in industrial vapor compression heat pumps are listed in Table 3. It can be seen from the table that when R142b, HTR01, and R134a are adopted in the heat pump, some negative effect (GWP) on the environment will occur. To the authors' knowledge, this is possibly the only negative effect of industrial heat pumps on the environment.

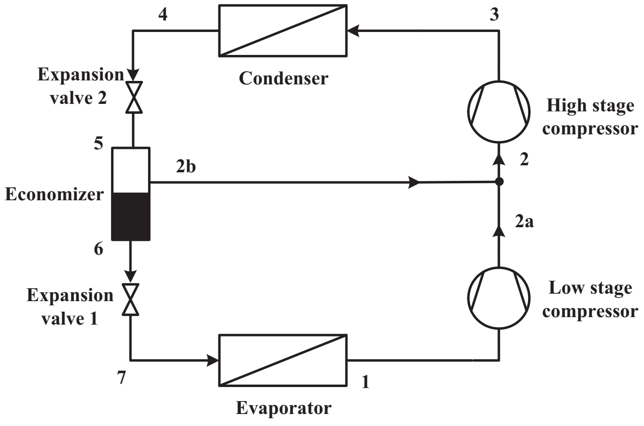
4. Research advances in industrial heat pumps in China

To meet the demand for high temperature and to achieve a higher COP, heat pump systems can have different components in their configurations. For example, the vapor compression cycles can be advanced to two-stage or multistage systems, and an economizer, an intercooler, and an ejector can be added to the cycles to improve energy efficiency [55–58]. The absorption cycles can also have two-stage systems and single or double-effect systems [59,60]. Moreover, two different heat pump systems can be combined together to generate a hybrid system. For example, a compression-absorption heat pump can be developed by combining a compression cycle and an absorption cycle [61]. Most of these different systems are used for waste heat recovery in China. The following sections will cover discussions on four aspects: the vapor compression system, absorption system, hybrid system, and chemical system.

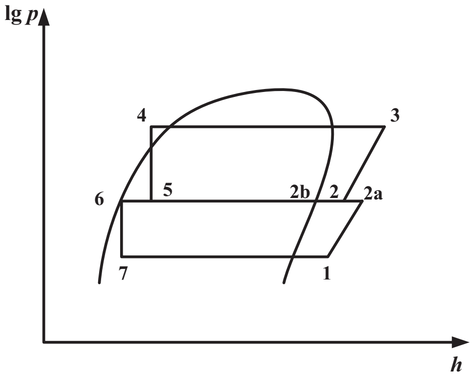
4.1. The vapor compression system

In situations where the temperature of the heat sink is much higher than that of heat source, a multistage vapor compression system can be employed. The multistage system has at least one high-stage compressor and one low-stage compressor. In each stage, different refrigerants may be used, and a reasonable pressure ratio can be achieved.

To get a higher COP and improve energy efficiency, an economizer and an intercooler can be added to the heat pump systems.

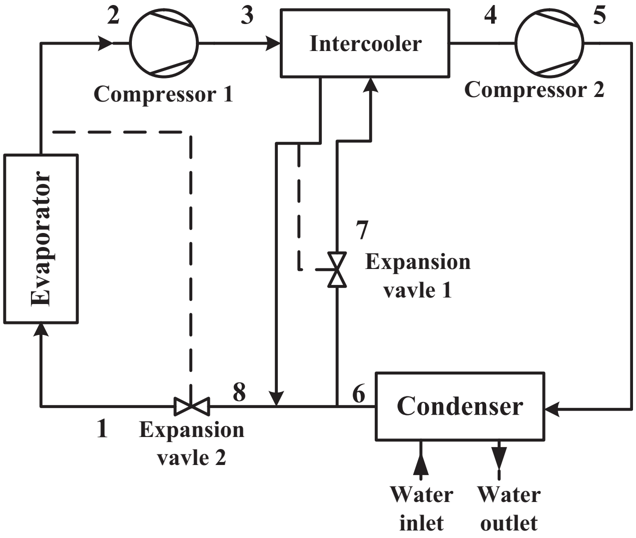


(a) Schematic diagram

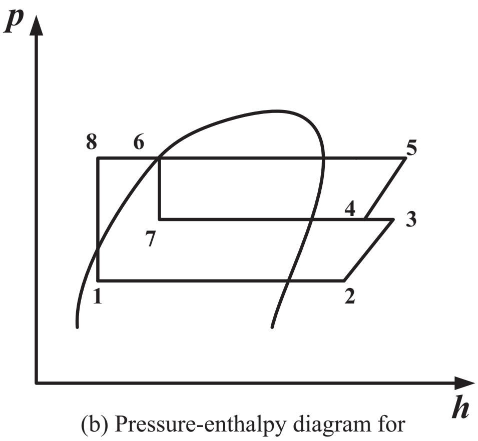


(b) Pressure-enthalpy diagram for thermodynamic cycle

Fig. 9. Two stage cycle with economizer.



(a) Schematic diagram

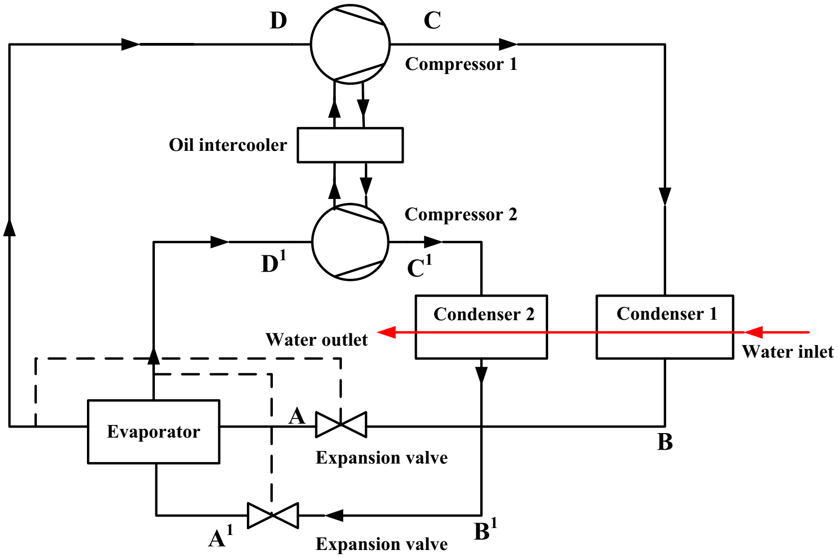


(b) Pressure-enthalpy diagram for thermodynamic cycle

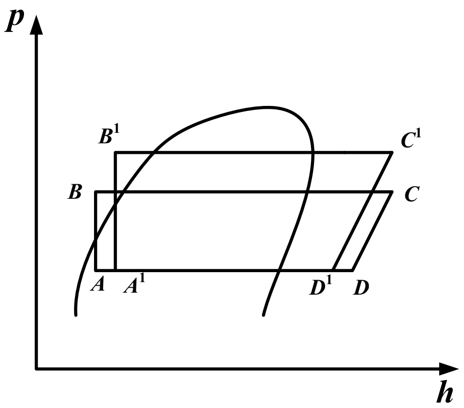
Fig. 10. Schematic of two stage cycle with intercooler.

The schematic of a two-stage system with an economizer, and the *p*–*h* diagram of its thermodynamic cycle are shown in Fig. 9. When the refrigerant enters the economizer, the vapor part of the refrigerant directly enters the suction line of the high stage compressor (process path 2b-2), where it gets mixed with the discharge vapor from the low stage compressor (process path 2a-2). This part of the vapor from the economizer does not go through the evaporator and the low stage compressor, and hence it is not necessary to compress it; this leads to some improvement in the COP [62]. Pan and Wang investigated the performance of a two-stage vapor compression heat pump with an economizer, and they found that compared with a single-stage system, the two-stage system has a better cycle performance. With the two-stage system having the economizer, with the optimal interstage pressure (defined as the saturated pressure of the refrigerant in the economizer), an increase in the COP up to 15.2% for HFC152a and up to 12.4% for HFC245fa is obtained compared with a single-stage system [63]. Cao et al. [64] tested the performance of a heat pump using an economizer vapor injection system at different mass ratios of R22/R60, and found that a better performance can be obtained with a 15% mass ratio of R600a, with the mixture refrigerant at lower temperature conditions. They also found that the heating capacity and energy efficiency ratio of the system with the mixing refrigerant can be improved by 20% and 15%, respectively, compared to the R22 system. Chen et al. [65] simulated and theoretically analyzed a high-temperature heat pump (HTHP) with a two-stage centrifugal compressor that utilizes produced water (a byproduct in an oil field, which is a type of waste heat) as the heat source; they concluded that HTHP can be an alternative to a water boiler that is used to heat viscous oils. Their simulated results demonstrated that the COP of the HTHP is 3.18, and that the HTHP would save over 15% energy compared with the situation where the heating is done by a boiler.

The schematic and the *p*–*h* diagram of a two-stage compression cycle with an intercooler are presented in Fig. 10. The performance of this cycle is better than that of the cycle with an economizer; however, the disadvantages of this cycle are the large pressure drop in the intercooler and the entrainment of liquid droplets. Wang et al. [66] presented a theoretical analysis and experiment study on a high-temperature heat pump with different configurations. Performance comparison among parallel cycles with serial heating on the water side, a two-stage compression cycle with intercooler, and a single-stage cycle was conducted. The calculation results proved that the performance of the parallel cycles with serial heating on the water side is better than that of the other two cycles when the condensing temperature is above



(a) Schematic diagram

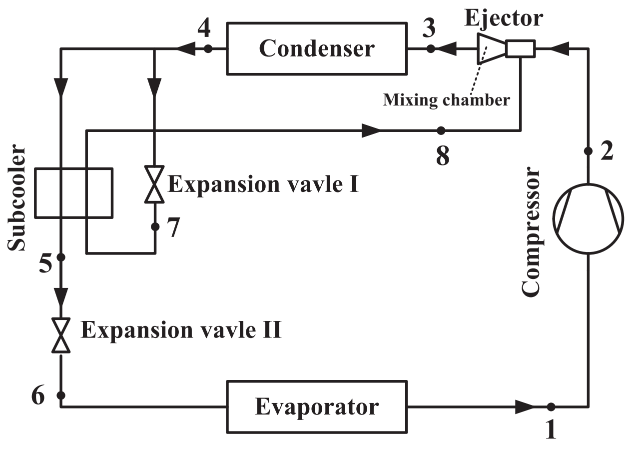


(b) Pressure-enthalpy diagram for thermodynamic cycle

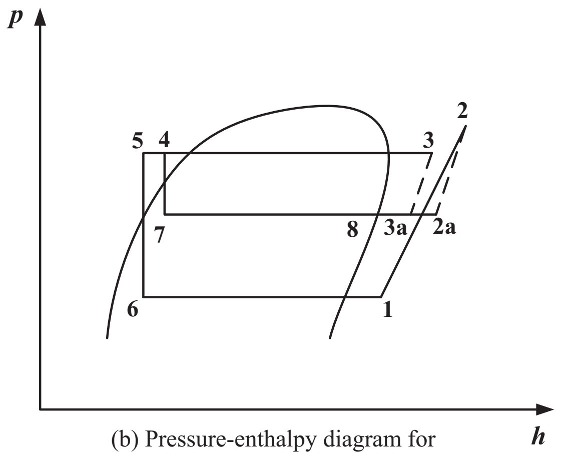
Fig. 11. Heat pump using parallel cycles with serial heating on the water side.

75 °C. The schematic of the heat pump using parallel cycles with serial heating on the water side and its p–h diagram are shown in Fig. 11, in which two compressors are arranged in two independent cycles, respectively, and two evaporators are arranged into one heat exchanger shell to reduce the volume of the parallel cycles. In this system, water is heated by the low-stage condenser to a certain temperature, and then it enters the high-stage condenser, where it is further heated. The experimental results show that the above system can provide hot water at temperatures above 85 °C with a COP of 4.3.

Many studies have been performed by employing an ejector to decrease the throttling loss and increase the COP of the system [67–71]. Chen et al. [68] proposed an innovative ejector enhanced vapor compression heat pump cycle that consists of a compressor, an ejector, a condenser, an evaporator, a subcooler, and two expansion valves. Fig. 12 shows the schematic of this cycle and its corresponding p–h diagram. In the p–h diagram, the process path (2-2a, 2a-3a, 3a-3) represents the working process of the ejector. The high pressure vapor refrigerant leaves the compressor as working steam (state point 2) and mixes with the vapor refrigerant (state point 8) from the subcooler (second steam) in the ejector. When the working steam flows through the nozzle, it reaches such a high speed that a local negative pressure is formed in the mixing chamber, and hence the working steam mixes with the second steam in the mixing chamber. The mixed steam (state point 3) enters the condenser where it condenses (state point 4), and then the condensed refrigerant separates into two streams: one flows through expansion valve 1 (state point 7) and enters the subcooler, in which the steam absorbs heat and evaporates, and then returns to ejector; the other is directly subcooled in the subcooler (state point 5), and then flows through expansion valve 2 (state point 6); then, it enters the evaporator, where the steam evaporates (state point 1) and enters compressor again. Compared with the conventional heat pump cycle, the new ejector system has a larger degree of subcooling and heating capacity. From their calculations, the COP and heating capacity of the new ejector system are improved by 1.62–6.92% and 15.2–37.32%, respectively, compared with those of the conventional heat pump cycle. Yu et al. [69] developed a new ejector enhanced vapor compression cycle using refrigerant R32. This cycle employs an ejector with two suction inlets to recover the expansion process losses of the cycle. They reported that the developed ejector cycle has 8.83–9.34% higher heating COP and 13.64–9.34% higher heating capacity than those of the basic vapor compression cycle over the range of evaporator temperatures. Xu et al. [70] studied the performance of an enhanced vapor injection (EVI) heat pump system employing R32, and they demonstrated that the EVI system has a higher heating capacity and a higher COP than a single stage heat pump system. The effect of high-side pressure on system performance of a transcritical CO_2 heat pump cycle with adjustable ejector was studied by Xu et al [71]. Bai et al. [72] proposed the integration of an injector, a subcooler, and a CO_2 heat pump, and this system is named as ejector enhanced sub-cooler vapor injection CO_2 heat pump cycle (ESCVI); they conducted energetic and exergetic analyses on the thermodynamic performance of the system. The analysis results showed that the COP and heating capacity of the ESCVI can be improved up to 7.7% and 9.5%, respectively, compared with the conventional vapor injection cycle with a sub-cooler (SCVI).



(a) Schematic diagram



(b) Pressure-enthalpy diagram for thermodynamic cycle

Fig. 12. Schematic of an ejector enhanced heat pump cycle.

Ma [73] proposed a cascade system named double-stage coupled heat pump (DSCHP), which is a combination of a conventional air source heat pump (ASHP) and a water source heat pump (WSHP) with a middle water loop, as shown in Fig. 13. Wang et al. [74] showed the results of their experimental study on this cascade system, and estimated that the energy efficiency and heating capacity of the system increase by 18% and 20%, respectively, compared to the ASHP. Shi et al. [75] established a thermo-economic model for the double-stage coupled heat pump, considering finite-rate heat transfer, heat leak losses, and internal irreversibility in the model. A theoretical foundation for performance analysis and optimization of the DSCHP, using the finite-time thermodynamics theory, was presented. They indicated that the optimized system can not only increase the heating capacity, but also provide high economic benefit; this result plays the role of a reference for preliminary design and optimization of real DSCHP systems.

Jiang et al. [76] introduced a trans-critical CO_2 water–water heat pump with tube-in-tube heat exchangers and a gas cooler. The experimental system is illustrated in Fig. 14. The performance of the CO_2 heat pump system with an internal heat exchanger (IHX) was compared with that of a conventional CO_2 heat pump system. The results showed that both COP and the relative capacity change index of the system with IHX are higher than those of the system without IHX. Furthermore, decreasing the CO_2 outlet temperature of the gas cooler is an effective way to improve system efficiency.

Pang et al. [77] analyzed the performance of a mechanical vapor recompression heat pump based on their test data, and they found that adiabatic efficiency decreases as the suction pressure increases, resulting in a decrease in the specific moisture extraction rate (SMER) and COP of the heat pump. When the suction pressure increases from 0.9 bar to 1.1 bar, the SMER decreases from 30.21 kg/kW h to 29.62 kg/kW h, while the COP drops from 23.41 to 22.99.

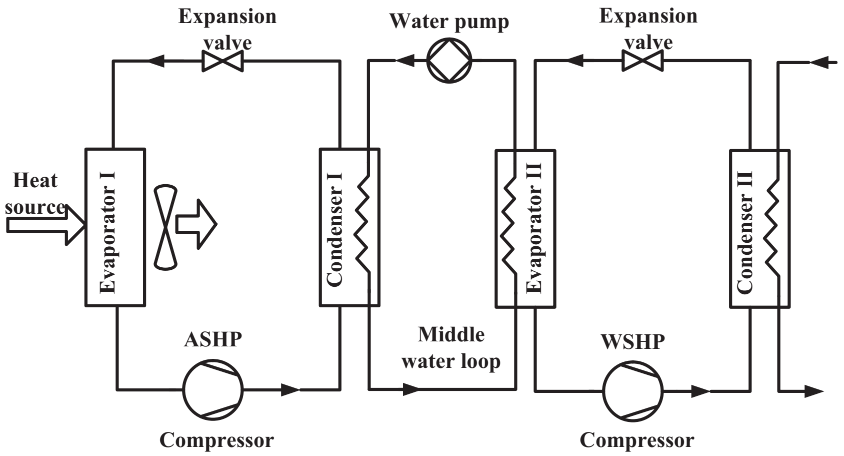
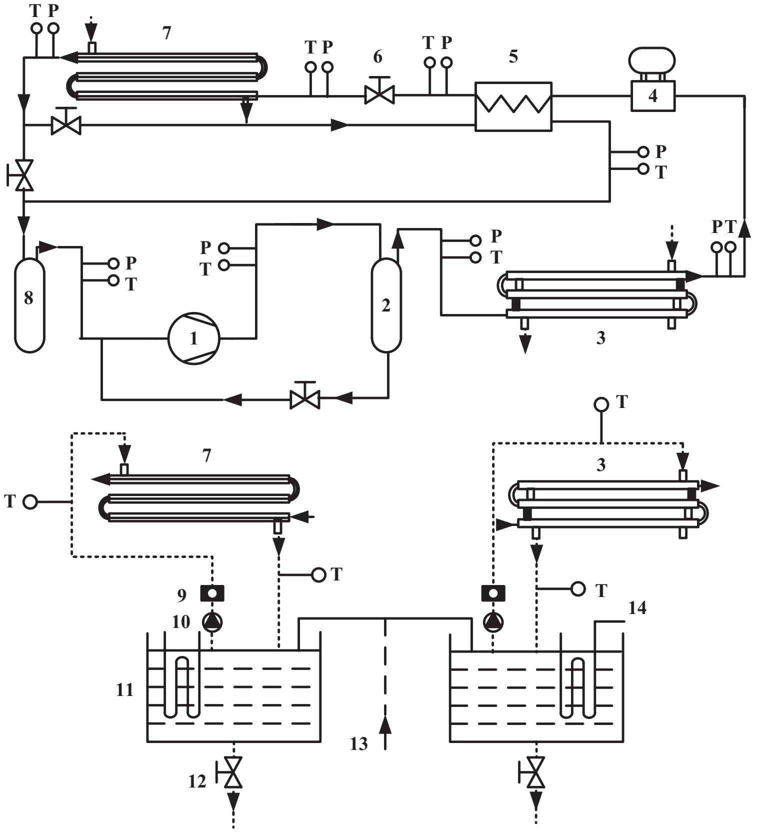


Fig. 13. Schematic of a double-stage coupled heat pump cycle.

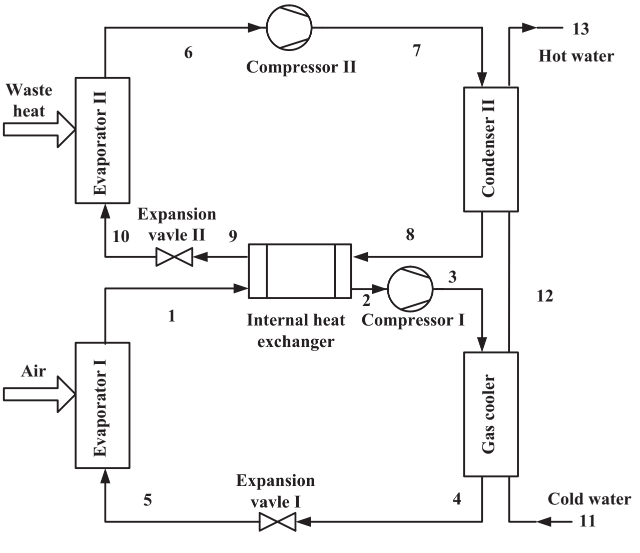


1 – compressor, 2 – oil separator, 3 – evaporator, 4 – mass flow meter, 5 – internal heat exchanger, 6 – throttling valve, 7 – gas cooler, 8 – gas–liquid separator, 9 – water flow meter, 10 – water pump, 11 – water tank, 12 – water discharge valve, 13– water supply, 14 – electric water heater, T – thermocouple, P – pressure sensor.

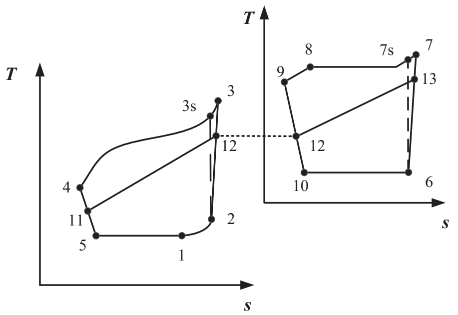
Fig. 14. Schematic diagram of experimental plant. 1 – compressor, 2 – oil separator, 3 – evaporator, 4 – mass flow meter, 5 – internal heat exchanger, 6 – throttling valve, 7 – gas cooler, 8 – gas–liquid separator, 9 – water flow meter, 10 – water pump, 11 – water tank, 12 – water discharge valve, 13– water supply, 14 – electric water heater, T – thermocouple, P – pressure sensor.

Cao et al. [78] of the present authors' group conducted thermodynamic and economic analyses of six different vapor compression systems. These are single-stage vapor compression heat pump (System 1), two-stage heat pump with an external heat exchanger (System 2), two-stage heat pump with a refrigerant injection (System 3), two-stage heat pump with a refrigerant injection and internal heat exchanger (System 4), two-stage heat pump with a flash tank (System 5), and two-stage heat pump with a flash tank and intercooler (System 6). They concluded that the COP and exergy efficiency of System 5 are similar to those of System 6, and that both the systems perform better than the other four systems. For example, at the evaporation temperature of 35 °C, the COP of systems 5 and 6 can reach approximately 4.2, while the COP of systems 3 and 4 is approximately 3.6, and the COP of systems

1 and 2 is only approximately 3.3. At the evaporation temperature of approximately 29 °C, the exergy efficiencies of the six systems reach the highest value in the evaporation temperature range of 25–35 °C, and the maximum exergy efficiencies of the systems are, 52.8%, 52.97%, 47.3%, 46.83%, 43.59%, and 44.1% for systems 6, 5, 4, 3, 2, and 1, respectively. In another paper, Cao et al. [79] proposed a high-temperature heat pump system having double-heat sources, with an internal heat exchanger, which is suitable for recovering waste heat and can produce hot water for industrial applications; the hot water can reach a temperature of 90 °C in this system. The schematic of the new system and its *T–s* (temperature–entropy) diagram are given in Fig. 15. This system is composed of two parts: the first part is an air source heat pump that uses CO_2 as the refrigerant; the second part is a heat pump employing R152a. The two parts are connected by an internal heat exchanger. In the first stage, CO_2 is heated by air and evaporates, then enters the internal heat exchanger, and is heated by R152a, which comes from condenser 2. Through compression, CO_2 condenses and releases heat in condenser 1, where the cold water is heated to a medium temperature. Meanwhile, R152a absorbs heat from the waste heat and evaporates, and then it gets compressed and condenses in condenser 2, where the medium-temperature water is upgraded to a higher temperature. Finally, the condensed R152a flows into the internal exchanger. The theoretical model of the new system for exergy analysis was established, and its thermodynamic performance was analyzed. For recovering the waste heat at 50 °C, the COP and exergy efficiency of the high-temperature heat pump with double-heat sources are higher by 41.9% and 23.96%, respectively, compared with the single source high-temperature heat pump.



(a) Schematic diagram



(b) Temperature-entropy diagram for thermodynamic cycle

Fig. 15. Double-heat sources high-temperature heat pump system with internal heat exchanger.

With regard to the vapor compression system, the Chinese researchers' contributions can be summarized as follows.

(1) To achieve the goal of improving COP and energy efficiency of system, some new equipment or new types of components are added to the conventional vapor compression system.

(2) To meet the requirement of users for higher temperature heat sources, some new systems based on the vapor compression system are proposed. The performance of the new systems is studied, and this information can provide a reference for new heat pump system design and optimization.

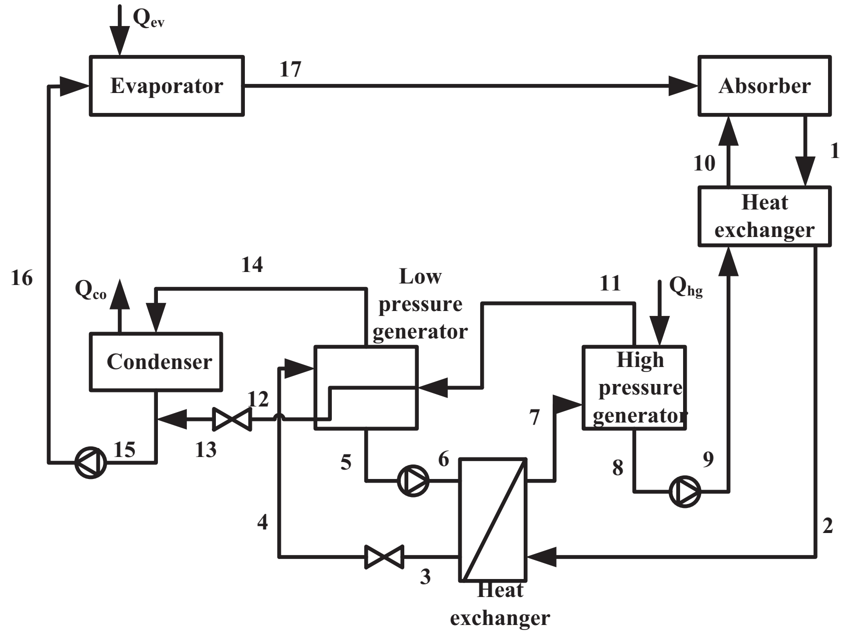
4.2. The absorption system

The absorption heat pump also plays an important role in recovering the waste heat generated in the industrial processes. Recently much attention has been devoted to this type of pump in China [80,81]. The following contents highlight a significant development in the application of the absorption heat pump in the industrial processes in China.

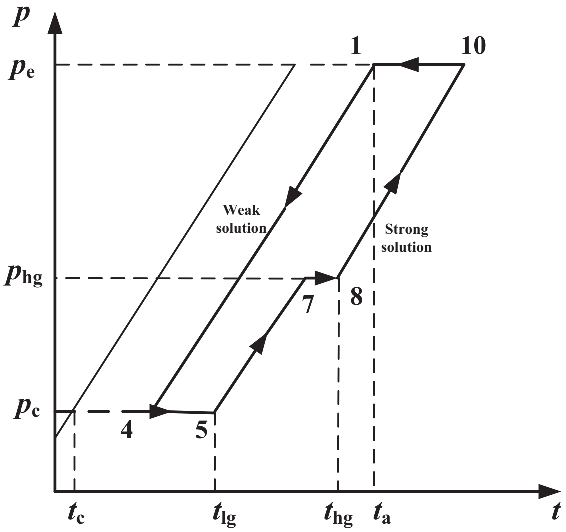
In 1999, the first industrial-scale (5000 kW) absorption heat pump, used in the conservation section, was built in the synthetic rubber plant of Yanshan Petrochemical Corporation, Beijing, China. The absorption system recovers waste heat from the steam stripping vapor mixture steam and organic vapor to heat hot water from 95 °C to 110 °C, and then the hot water returns to the coagulator as a heat source. Ma et al. [28] from Institute of Chemical Engineering, Dalian University of Technology performed a theoretical model analysis and experimental study on the absorption system. The simulated and experimental results proved that the mean COP of the system is 0.47, and the maximum temperature rise can reach 25 °C. After the absorption heat pump was installed, the consumption of steam per ton of rubber reduced from 2.53 t to 1.04 t. As an extension of this work, two sets of 7 MW absorption heat pump units were built subsequently.

Apart from the single-stage absorption heat pump consisting of an absorber, a generator, an evaporator, and a condenser, the double-effect absorption heat pump has also been used in waste heat recovery; it consists of two generators, a high-pressure generator, and a low-pressure generator. Zhao et al. [82] proposed a double-effect absorption heat pump using TFE/E181 as the working fluid and conducted a simulation study. The schematic and *p–t* diagram of the double-effect absorption system are shown in Fig. 16. In the *p–t* diagram, the process path 1-4-5-7-8-10 represents the circulation of TFE/E181 solution. From the simulated results, it can be noted that when the temperature of the high-pressure generator is above 100 °C and the gross temperature rise is 30 °C, the COP of the double-effect absorption system can reach 0.58, while that of the single-stage absorption system is only 0.48, which means approximately 20% increase in the COP of the double-effect absorption system. They also simulated the double-effect absorption system using LiBr/H_2O instead of TFE/E181, and obtained a COP of 0.64. In addition, they observed that with the increase in the absorption temperature, the COP of the double-effect absorption system decreases faster than that of the single-stage absorption system. Therefore, a double-effect absorption heat pump will be more suitable for situations where the heat source is of high temperature and only a small temperature rise is needed.

A numerical model of the falling film absorption process in an absorber was developed by Bo et al. [83] from the same research group as in Ref. [82], and the effect of variable physical properties



(a) Schematic diagram



(b) Pressure-temperature diagram

Fig. 16. Schematic of a double-effect absorption heat pump cycle.

on the absorption process was analyzed by them. They also simulated the vapor absorption by wavy lithium bromide aqueous solution films, and concluded that solitary waves can enhance heat transfer, and also strengthen the absorption process [84].

Zhang et al. [85] tested the performance of an open absorption heat transformer (OAHT) combined with single-effect or multi-effect distillation (Fig. 17). In the OAHT, the condensed water from the condenser is directly discharged instead of being pumped into the evaporator, which is different from the process in a conventional closed absorption heat pump. The system can be used to distill waste water from heavy oil production, and the distilled water can be supplied to a steam boiler. By means of this system, waste heat (at approximately 70 °C) can be upgraded to a higher level (125 °C).

Yang et al. [86] introduced four types of double-stage absorption heat pumps using LiBr/H_2O to recover waste heat: series-flow type, reverse series-flow type, parallel-flow type, and reverse parallel-flow type. They built the thermodynamic and heat-transfer simulation models of the four types of absorption heat pumps, with the heat-transfer simulation model based on the thermodynamic simulation results. The effects of the driving heat source (steam) input pressure, the waste heat outlet temperature, and the hot water inlet temperature on the thermal efficiencies of the four systems were simulated. It was proved from the simulation results that the effects of the three factors on the performance of the four systems have the same trend. A comparison of the performance of the systems showed that the parallel-flow type is worse than the reverse parallel-flow type, which performs the best, and that the series-flow type and reverse series-flow type have almost the same performance, a little worse than the parallel-flow type. Besides, they conducted studies on the economical optimization of double-stage LiBr absorption heat pumps by using the orthogonal design method, and the life cycle cost (LCC) was also considered in the optimal design [87].

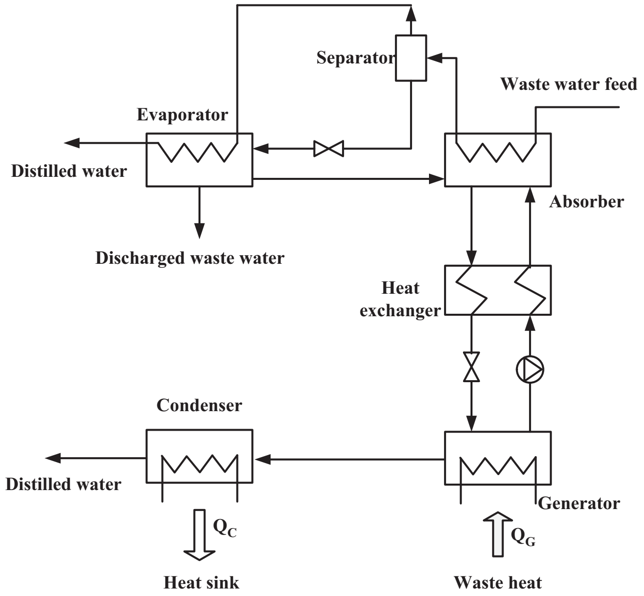


Fig. 17. Schematic diagram of a single-effect distillation integrated with an open AHT.

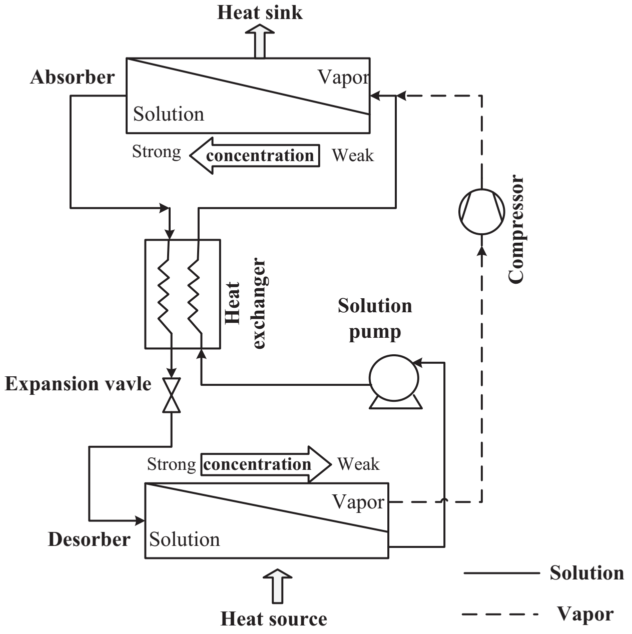


Fig. 18. Schematic of an NH_3/H_2O compression-absorption hybrid heat pump based on a single-stage vapor compression cycle.

It can be seen from the above that the applications of the absorption heat pump system for waste heat recovery in China had started 15 years ago, and both experimental studies and numerical simulation have been widely conducted. The following are the major conclusions from these results. The COP of the double-effect absorption pump is higher than that of single-effect absorption pump, but the double-effect pump is more suitable for situations where the heat source is at a high temperature, and only a small temperature rise is needed. As far as the configuration of the two-stage absorption heat pump is concerned, the reverse parallel-flow type is the best; then comes the parallel-flow type, and finally the series-flow type. As the driving power of the absorption heat pump is heat, and not electricity, this system is preferred in situations where waste heat is abundantly available, while the cost of electricity is high.

4.3. The hybrid system

The hybrid heat pump is a combination of two different heat pump cycles by which the performance of the system can be improved. The compression–absorption heat pumps [88,89] and solar-assisted heat pumps are two typical hybrid systems [90–92].

Fig. 18 shows an NH_3/H_2O compression–absorption hybrid heat pump based on a single-stage vapor compression cycle [88]. Wang and Du [89] studied an NH_3/H_2O compression–absorption heat pump, and compared it with the NH_3 vapor compression heat pump by theoretical analysis and calculations. Their analysis showed that under the same operating conditions, the COP of the NH_3/H_2O compression–absorption cycle is less than that of the NH_3 vapor compression cycle, but the NH_3/H_2O compression–absorption cycle offers a higher heat-supply temperature. The compression ratio of the compressor is greatly reduced when a heat source with higher temperature is offered; this can improve system safety.

Pei et al. designed and built a heating system of high-temperature biogas digester in which solar energy and methane liquid were used as the heat sources for the heat pump [90]. The optimization of a combined system using solar energy and heat pump, for wood drying, was conducted by Zhang et al. [91]. In north China, the water contents of agricultural products are above the safe storage moisture levels when the agricultural products are harvested. Therefore, Xie et al. [29] have proposed a solar assisted heat pump (SAHP) drying system with a storage tank so as to dry the products and make them easy for storage. The system is shown in Fig. 19. They investigated the performance of the SAHP drying system and noted that the COP of the SAHP drying system is 5.369, while it is 3.411 without solar energy. Moreover, the storage tank was developed to solve the problem of mismatch between the solar radiation and the energy demand caused by the intermittence of the solar energy. The paper gave some guidance on the application of the solar assisted heat pump system for drying the agricultural products. The solar assisted heat pump can improve the drying quality; however, its application in China is limited compared to its applications abroad, owing to its high construction cost.

The studies on the hybrid system conducted in China so far are less than those for the vapor compression system and the absorption system. Because of its special advantages for industrial applications, more attention needs to be paid to the hybrid system in the future, especially the solar assisted heat pump.

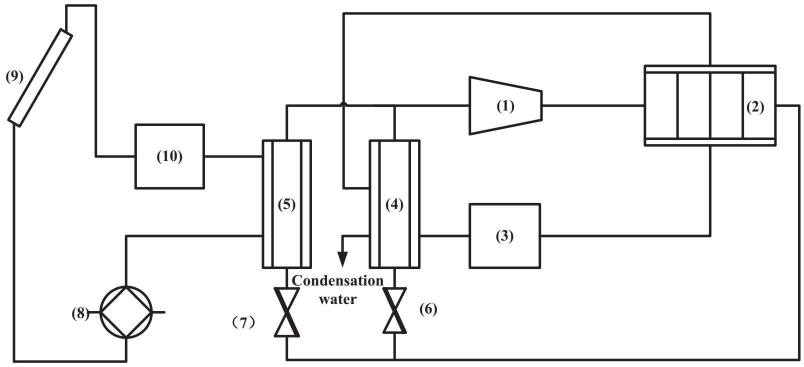
4.4. Chemical heat pump

As an environment friendly system, the chemical heat pump has attracted a lot of attention in the recent years in China. Several studies have been conducted on the isopropanol–acetone–hydrogen (IAH) chemical heat pump by Huai et al. [92–95]. The IAH chemical heat pump mainly consists of an exothermic reactor, an endothermic reactor, a distillation column, a regenerator, a condenser, and a reboiler, as shown in Fig. 20 [92]. In this system, low temperature heat is supplied to the reboiler and endothermic reactor, and the dehydrogenation of isopropanol takes place in the endothermic reactor. The reaction equation can be written as

$$(CH_3)_2CHOH(g) \rightarrow (CH_3)_2CO(g) + H_2(g)$$

(input of low-grade heat)

The high temperature heat is released by exothermic reaction in the exothermic reactor, and the equation for the reaction is as follows.



Note: (1). a variable-speed compressor (2). air-cooled condenser (3). dry unit (4). dehumidifier (5). evaporator (6). expansion valve (7). expansion valve (8). water pump (9). solar collectors (10). energy storage tank

Fig. 19. A solar-assisted heat pump drying system (SAHP) with an energy storage tank. Note: (1) a variable-speed compressor. (2) Air-cooled condenser. (3) Dry unit. (4) Dehumidifier. (5) Evaporator. (6) Expansion valve. (7) Expansion valve. (8) Water pump. (9) Solar collectors. (10) Energy storage tank.

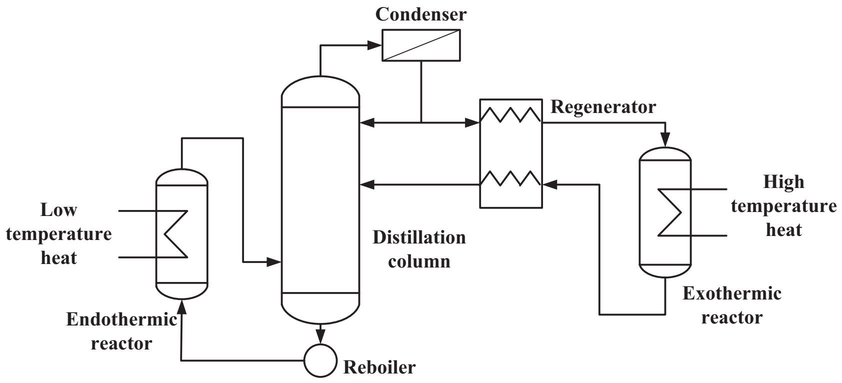


Fig. 20. The schematic diagram of Isopropanol–Acetone–Hydrogen chemical heat pump.

$$(CH_3)_2CO(g) + H_2(g) \rightarrow (CH_3)_2CHOH(g)$$
$$\text{(output of high-grade heat)}$$

In the IAH chemical heat pump, the heat transmission between the low temperature level (50–80 °C) and the high temperature level (200 °C) is based on the reversible chemical reaction. The design optimization of the IAH chemical heat pump was conducted using the entransy theory [96,97], and the results showed that the entransy concept is helpful in the optimization design [92]. They also studied the optimization design of the recuperator in a chemical heat pump by applying the entransy dissipation theory [93]. As an extension of the work mentioned above, they conducted thermodynamic analysis of an IAH chemical heat pump using the software ASPEN Plus. The performance of the IAH chemical heat pump was investigated using the following six evaluation criteria: enthalpy efficiency, entransy efficiency, entropy generation number, revised entropy generation number, exergy efficiency, and ecological COP, and different or contrary conclusions were obtained with different evaluation criteria. The results showed that the performance of the chemical heat pump improves with a decrease in the distillation to feed ratio, based on the first and second laws of thermodynamics. With the increase in the endothermic reaction temperature, the performance of the chemical heat pump improves from the viewpoint of the first law of thermodynamics; however, the performance worsens from the viewpoint of the second law of thermodynamics. The entransy efficiency is similar to integrate the enthalpy efficiency and exergy efficiency on the performance evaluation, and the revised entropy generation number makes a more accurate response when compared with entropy generation number [94]. Hence, further studies in this regard are required.

The idea of using a reactive distillation column instead of the endothermic reactor for the liquid phase dehydrogenation of isopropanol was introduced in the Ref. [95]. The experimental study on the liquid phase dehydrogenation of isopropanol in a reactive distillation column was conducted, and the results indicated that this process needs less energy, and that it is more efficient than using the reactive distillation part. It was also found that the amount of catalyst, the temperature of the heat source, and the reflux ratio have significant effects on the hydrogen produced and the separation of acetone and isopropanol during the reactive distillation.

4.5. Heat exchangers used in heat pumps

A number of investigations have been conducted on the heat exchangers of heat pump systems [98–102]. Improving the performance of the evaporator or condenser is an effective approach to enhance energy efficiency and performance of the heat pump. Shen et al. [98] proposed a novel dry-expansion shell-and-tube evaporator with a de-fouling function, suitable for use in waste heat recovery. Subsequently, they conducted experiments on the novel evaporator and a conventional immersed evaporator with the same wastewater source heat pump, and compared the results; they found that the novel evaporator has a heat transfer coefficient 3.1 times that of the immersed evaporator on the waste water side, while it has a more compact structure under the same heating capacity [99]. Subsequently, they developed a steady-state model for the novel dry-expansion shell-and-tube evaporator; this model can be applied to predict the evaporator performance [17].

To design a heat exchanger that can match the high-temperature heat pump, a design method based on the performance of the complete heat pump system is proposed by Li et al. [100]. Using this design method, the effects of the configuration and the area of the heat exchangers on system performance have been studied. The results showed that the ratio of the areas of the evaporator and condenser has an optimal range when the configurations of the heat exchange tubes have been selected. Zhao et al. [101] developed a new optimal design method for heat exchangers in a two-stage high-temperature heat pump system; this method can solve the problem of mismatch of different components. Moreover, the method is also applicable to other similar heat pump systems.

Heat exchanger is the common component in different types of heat pumps. For the purpose of comparison, the types of heat exchangers used in different heat pump systems covered in this study are summarized in Table 4.

4.6. Comparison of different industrial heat pumps

The vapor compression cycle that consumes some mechanical or thermal energy is widely applied and can meet the requirement of different temperature demands (up to 120–130 °C). Several refrigerants can be used with this cycle and the heat pumps can be of different capacities and sizes.

The absorption heat pump is driven by a heat source, which is different from the vapor compression cycle, which uses mechanic energy as the drive source. Because of the limitation in the achievable delivery temperature, the absorption heat pump (type I) can be used in the industrial process only in cases where the heating temperature is below 100 °C. The heat transformer (type II), which uses medium and high-temperature waste heat as the heat source, can generate a higher delivery temperature (100–150 °C). Although the absorption heat pump is also available in all industrial sizes, the large size is preferred considering the techno-economic performance.

The hybrid heat pump can improve the performance of the system. The solar assisted system has the advantages of energy saving and environmental protection, and is recommended for use in drying applications.

The chemical heat pump is environment friendly and can provide a high delivery temperature; hence, it is suitable for industrial

Table 4
Heat exchangers used in industrial heat pumps.

Heat exchanger type	Application in the heat pump system	Heat pump type
Shell-and-tube heat exchanger	Condenser [31]	Vapor compression cycle
	A dry-type shell-tube evaporator a flooded type condenser [44]	Vapor compression cycle
	Dry-expansion shell and tube evaporator; water-cooling condenser [48]	Vapor compression cycle (high temperature)
	Flooded evaporator, horizontal shell and tube condenser [65]	A high temperature heat pump system with two-stage centrifugal compressor
	Evaporator; condenser [66]	Vapor compression cycle (high temperature)
	Evaporator [67]	An enhanced vapor injection heat pump
	Condenser [75]	Double-stage coupled heat pumps
	A vertical shell-and-tube type condenser [28]	Absorption heat transformer
	Vertical falling liquid film (absorber, generator, evaporator) [81]	Absorption heat transformer
	Each component [86]	Double-stage LiBr Absorption Heat Pumps
	A novel dry expansion shell-and-Tube evaporator with a de-fouling function [17,98,99]	Waste water source heat pump
Immersed heat exchanger	Evaporator [99]	Waste water source heat pump
Fin-and-tube heat exchanger	Evaporator [64]	Heat pump using economizer vapor injection system
	Evaporator [74]	Double-stage coupled heat pumps
Plate heat exchanger	Aplate fin evaporator [31]	Vapor compression cycle
	Condenser [70]	An enhanced vapor injection heat pump
	Nickel-brazed plate heat exchangers (absorber, desorber) [88]	Compression/absorption high-temperature hybrid heat pump
Spiral plate heat exchanger	Solution heat exchanger [28]	Absorption heat transformer
Double-tube-type heat exchanger	Condenser, evaporator [40]	Vapor compression cycle
Tube-in-tube heat exchanger	Condenser [64]	Heat pump using economizer vapor injection system
	Evaporator [67]	Transcritical CO_2 heat pump system with ejector
	Evaporator, gas cooler [76]	Trans-critical CO_2 water–water heat pump
Coaxial pipe heat exchanger	Evaporator, condenser [45,47]	Vapor compression cycle

Table 5
Techno-economic comparison of industrial heat pump types.

Industrial heat pump type	Maximum sink temperature (°C)	Maximum temperature lift (°C)	Scale (MW)	Installation costs (Yuan/$kW_{heat\ output}$)
Vapor compression	120	80	0.3	1.25×10^3
			2.3	1.65×10^3
Absorption, type I ($LiBr/H_2O$)	100	50	3	1.95×10^3
Heat transformer, type II ($LiBr/H_2O$)	150	60	5	1.92×10^3

applications. However, research on this type of pump is still in the laboratory stage in China. Much effort needs to be devoted to the industrial applications.A techno-economic comparison of different types of industrial heat pumps in China is presented in Table 5.

5. Application examples of industrial heat pumps in China

The ability of industrial heat pumps to recover waste heat and possess high energy efficiency makes them attractive in industrial applications, such as oil field exploitation, drying of fruits and vegetables, drying of tobacco and lumber, and chemical production. Some examples of industrial heat pumps used in the industrial field in China are presented in Table 6.

In the application design of industrial heat pumps, normally three problems have to be solved: selection of heat pump type and determination of its capacity, calculation of COP for the designed system, and estimation of the investment payback time. For discussing these three problems, five typical examples of the usage of industrial heat pumps in three industrial applications are selected, and their performances are discussed in detail below. The heat pump applications considered are, those in the drying of wastewater sludge (one example), in crude oil heating of oilfields (one example), and in printing and dyeing (three examples). The emphasis in each of the these examples is different: in the example of the drying of wastewater sludge, mainly the calculation of heat output and the selection of pump type are discussed; in the example of crude oil heating of oilfields, the COP of the heat pump used in the oil field is calculated, and its energetic and exergetic analyses are also discussed; finally, an example in printing and dyeing is analyzed with focus on the calculation of the payback period for the heat pump investment.

5.1. Application in drying of wastewater sludge

With the economic development and accelerating urbanization in China, the throughput of municipal wastewater has increased rapidly, so the number of sewage plants has also increased. Statistics shows that 2630 sewage plants had been built before September 2010, and the throughput of the sewage can reach up to 1.22×10^8 m^3 per day [117]. As a byproduct of wastewater, the sludge contains rich parasite, pathogen, virus, heavy metal, etc. The sludge will pollute the atmosphere and water if it is not treated well; it threatens the environment and health of human beings, so the people and the society are increasingly concerned about the treatment of the sludge. The treatment of sludge follows the principle of stabilization, reduction, and harmless recovery of the resources. The processing methods of sludge include sanitary landfill, composting treatment, incineration, and land use. The land use is the recognized method; before land use, the sludge is to be pretreated. The most common pretreatment technology is thermal drying of the sludge. When the drying temperature is under 100 °C, the release of benzene series is much lower than that at a higher drying temperature. Thus, it is better to conduct thermal drying of the sludge at a lower temperature, so that the release of benzene series can be reduced to the maximum extent, and the danger of carcinogenic formation can be reduced [118]. The temperature that a normal industrial heat pump can provide is suitable for this purpose.

Drying technology that uses heat pumps, which is a recognized green drying technology, can save energy and reduce the discharge of waste gas; it has been widely used in applications such as drying of lumber, grain, fruits, and industrial raw materials [119,120]. However, sludge drying is a relatively new application of the industrial heat pump, and only a limited number of studies and applications are known to the present authors. These studies are briefly reviewed here. Shandong Fuhang New Energy Environmental Technology Corporation, Shandong, China developed thermal drying technology using solar assisted heat pump, and the corporation cooperated with the government of Yu city to build a sludge disposal center with a throughput of 20 t/d [121]. Rao et al. [112] analyzed the performance of a solar assisted heat pump system for sludge drying, and the results showed that with regard to economic benefit, the performance of the solar assisted heat pump is better than that during the process of heating by oil, gas, or electricity; moreover, there will be almost no peculiar smell in the whole process. A printing and dyeing industrial park in Xintang town of Guangzhou city conducted a waste water treatment project in which a solar assisted heat pump was applied to dry the sludge [122]. The schematic of the solar assisted heat pump built in Yu city of Shandong is more or less similar to the system (Fig. 21) presented by Slim et al. [123]. As shown in Fig. 21, the drying system consisted of a greenhouse, a sludge mixing engine, and two heat pump systems. The two heat pump systems were used to heat the air and the floor of the greenhouse: the air heat pump used the wet air as the heat source to upgrade the temperature level of the ambient air that is pumped in the greenhouse; the other heat pump used the treated waste water as the heat source to dry the sludge with the heating of the floor.

Apart from the solar assisted heat pump, another way to increase energy utilization efficiency is to use the thermal energy

Table 6
Application examples of industrial heat pump in China.

Industry	Process	Heat pump type	Heat supply temperature
Huabei oil field [100,115]	Crude oil transportation	Absorption heat pump	~80 °C
Liaohe oil field [102]	Crude oil transportation and space heating	Vapor compression cycle	55–60 °C
Daqin oil field [103]	Crude oil transportation and space heating	Vapor compression cycle	60–65 °C
Printing and dyeing [26]	Heating process of dyeing and soaping	Vapor compression cycle	95 °C
Printing and dyeing [27]	Wash-water heating and supply for boiler	Vapor compression cycle	85–90 °C
Printing and dyeing [104]	Heating process of dyeing	Vapor compression cycle	40–50 °C
Tobacco [105]	Tobacco heating	Vapor compression cycle	~68 °C
Tobacco [106]	Tobacco heating	Solar assisted heat pump	~80 °C
Salt [107,108]	Evaporation concentration	Vapor compression cycle	–
Rubber [109]	Condensation system heating	Absorption heat pump (Type II)	102 °C
Rubber [28]	Coagulator heating	Absorption heat pump (Type II)	110 °C
Power plant [110]	Back water heating	Absorption heat pump (Type I)	82 °C
Chemicals [111]	Polypropylene plant heating	Thermal vapor recompression cycle	–
Sludge [112]	Sludge drying	Solar heat pump	~85 °C
Chemicals [113]	Concentration of ammonium phosphate solution	Thermal vapor recompression cycle	–
Yoghurt [114]	Cleaning of product line	Vapor compression cycle	80–85 °C
Iron mine [115]	Antifreezing	Vapor compression cycle	–
Galvanizing line [116]	Process heating	Vapor compression cycle	70–75 °C

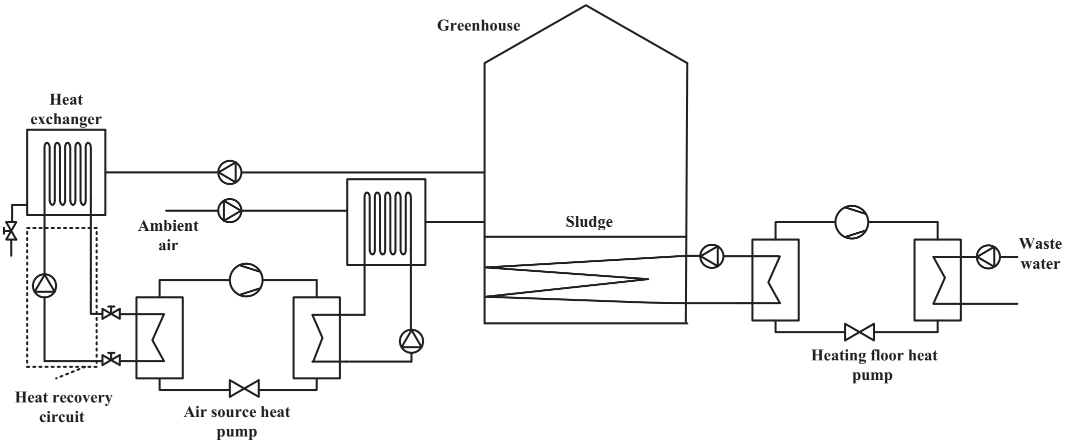


Fig. 21. Schematic diagram of the solar and heat pump sludge drying system.

contained in the sewage. The municipal sewage plant is the place where the waste water is disposed, and sludge is produced here. The waste water contains a large amount of low-temperature thermal energy, which can be continuously supplied. A better method of utilizing the resources in a sewage plant is to use the waste water as the heat source for the heat pump. Tian et al. [124–126] studied the heat pump used in anaerobic digestion of municipal wastewater sludge, and proposed a method of comprehensive utilization of the resources in a sewage plant. Using the secondary effluent from the sewage plant as the heat source, the heat pump can produce medium temperatures of 60–70 °C. The wastewater source heat pump is used not only for the anaerobic digestion of the sludge, but also for heating and cooling the factory area. The system can meet the temperature requirement of anaerobic digestion, and at the same time produce methane, which can be used in the sewage treatment system. The system can reduce the energy consumed in the sludge treatment and space heating, and can save approximately 30% and 40% energy in summer and winter, respectively.

This section covers the quantitative analysis of energy utilization efficiency of the sludge drying process that uses a heat pump. Taking a medium sewage plant in Xi'an as an example, the low temperature wastewater discharged from the plant is used as the heat source, and a sludge drying system using a heat pump is designed and the heating capacity is calculated. After mechanical dewatering, the sludge is transported by a screw pump to the greenhouse with a hot water radiant heating floor system. The sludge is heated by the heat pump through the floor and mixed using a sludge mixing engine, which gradually removes the moisture from the sludge by evaporation, and dries the sludge.

The sewage plant discharges waste water at the rate of 20×10^4 t/d, and the sludge in it at approximately 150 t/d. The moisture content of the sludge is 80% and 40% before and after the treatment, respectively, and the heat source is a heat pump that heats the sludge through a radiant heating floor system. Because of the low temperature in winter, which is the most disadvantageous season for sludge drying, the heat balance calculation must ensure that the demand in winter is also met. Thus, the winter weather data of Xi'an is taken as the design basis: i.e., ambient air temperature of 3 °C, humidity of 70%, and humidity ratio of 3.5 g/kg. The treatment temperature of the sludge is 60 °C, and the exhaust parameters are assumed as follows: temperature of 40 °C, humidity of 80%, and humidity ratio of 39 g/kg.

The schematic of the heat pump sludge drying system is shown in Fig. 22. The floor of the greenhouse is made up of three layers: the deepest layer consists of polystyrene board to reduce heat dissipation toward the ground; the second layer is composed of polyethylene tubes that are fixed on the polystyrene board; the top layer is made of concrete. In conjunction with the other insulation methods, the heating efficiency of the house is taken as 85%. The greenhouse needs ventilation, so that the vapor from the sludge surface is taken away in time to improve the mass transfer rate of the water in the sludge. The air supply outlet lies at the lower side of the greenhouse, while the air outlet lies at the top, and the ventilation system is composed of a fan and an air duct. The ventilation rate of fresh air in the greenhouse is 32.6 kg/s. With these parameters, the actual heating capacity of the heat pump sludge drying system is calculated as 5629.7 kW.

Four SHP-C2058G heat pumps, each having a heating capacity of 2056 kW, are applied on the basis of the calculation; one of the four heat pumps is kept as a reserve. The heat pumps use R134a as the refrigerant, and each pump contains a semi-hermetic screw compressor and a flooded evaporator. Using the waste water of the sewage plant as the heat source, the heat pump can produce hot water with a temperature of 65 °C with a COP of 3.2.

5.2. Application in crude oil heating in oil fields

In China, the exploitation of the main oil fields is already in high water cut period, and the liquid produced in the Daqin, Shengli, and Liaohe oil fields has only approximately 10% oil content, while the rest of the produced liquid is water. At present, plenty of oily sewage is reused by injecting the water into the wells, but the sensible heat of the sewage has to be recovered for saving energy. In some production processes of oil, such as in oil-water separation and crude oil transportation, thermal energy is needed to heat the crude oil, so that its viscosity can be reduced and the transport efficiency can be improved. Conventionally, such thermal energy is provided by a heating furnace, which consumes a lot of oilfield gas or crude oil. The heating furnace can be replaced fully or partially by an industrial heat pump by employing the waste heat as the heat source. It can not only save energy, but also avoid thermal pollution of the oily sewage discharge, thus providing both energy conservation and environmental protection benefits.

At present, several large-scale oilfields in China have utilized heat pump technologies. The following are some examples. An absorption heat pump system was installed in a combination station of the first oil production plant in Huabei oilfield, and the system can produce hot water with temperature above 85 °C [101]. Xianhe and Gudong Oil Production Plant of Shengli oil field uses the H series (named by the corporation) heat pumps provided by Beijing Qingyuanshiji Technology Corporation, and the heat pumps produce hot water with temperature above 85 °C to heat the crude

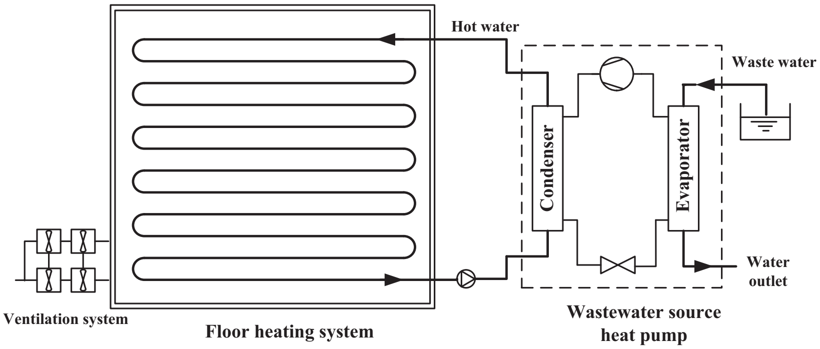


Fig. 22. Schematic diagram of the wastewater heat pump sludge drying system.

oil. Shensi combination station of Liaohe oil field reuses oily sewage at 50 °C as the heat source for the heat pump, and it can produce hot water with temperature above 80 °C, which is used for process heating. Twenty two heat pump systems have been cumulatively applied in the Daqin oil field since the heat pump technology was introduced first in 2002; these systems save a large amount of coal [30,102]. Xiaolongwan pumping station, located in the Liaohe oil field, was transformed in 2011, and two original heating furnaces were replaced by water source heat pumps, which can save approximately 1100 t crude oil per year [103]. A detailed introduction and analysis will be given below on Lusheng combination of Shengli oil field.

The Lusheng gathering station, Shengli oil field includes oil unloading, treatment, and transport; it was built in 1998. After extension three times, the treatment scale of the combination has reached up to 5 × 10^5 t/a, and 120 t of high temperature vapor per day is needed for dehydration and heating of the crude oil. The vapor is purchased from a nearby power plant. On the other hand, the station discharges 4660 t sewage at 47 °C and 1000 t sewage at 80 °C per day, which leads to serious wastage of thermal energy. To reduce energy consumption and production cost, the original crude heating system of the station was modified. The transformed crude heating system is shown in Fig. 23. In the transformed system, the high temperature (80 °C) sewage is directly used for primary heating of the unloading oil, and the low temperature (47 °C) sewage is used as the heat source for the heat pump, which produces hot water with a temperature of 90 °C, and the hot water is used to further heat the primary unloading oil to the transport temperature. It can be seen that the system takes advantage of the waste heat in the oily sewage, and not only meets the requirement of oil dehydration and transport heating, but also partly meets the requirement of space heating.

The heat pump used in the transformed crude oil heating system is an LiBr/H_2O absorption heat pump, which is a type I absorption heat pump, because burning natural gas is used as the driving heat source [127]. The heat pump consists of an absorber, an evaporator, a condenser, a generator, an expansion valve, two canned pumps, and a solution heat exchanger. An image of the pump is shown in Fig. 24. The evaporator, condenser, generator, and absorber are all shell and tube heat exchangers, while the solution heat exchanger is a plate heat exchanger. Fig. 25 illustrates the schematic of the type I absorption heat pump system used in Lusheng gathering station. In this system, the waste heat of the sewage (38.8 °C) is recovered and upgraded to a high temperature level, and then the heat of the sewage at the high temperature level is released by the absorber and condenser to produce hot water having a temperature of 86.4 °C. The hot water is applied to heat the crude oil to 80 °C, and it can also meet the requirement of space

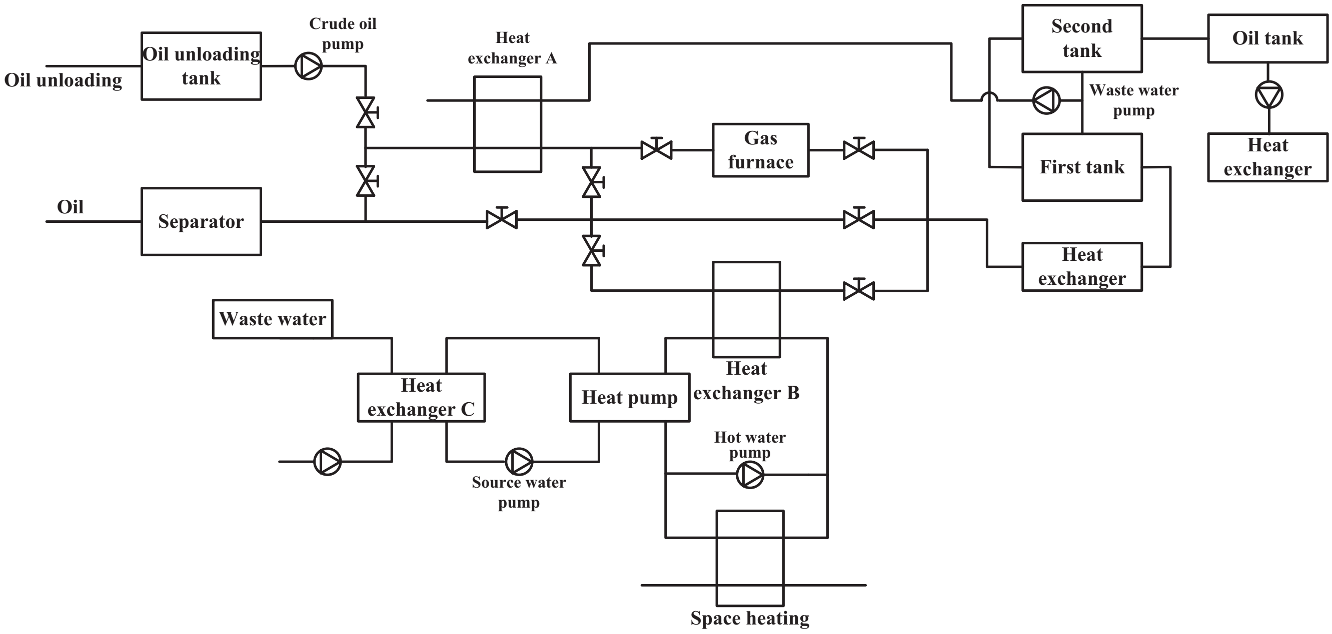


Fig. 23. Diagrammatic flowsheet of a wastewater heating system for crude oil.

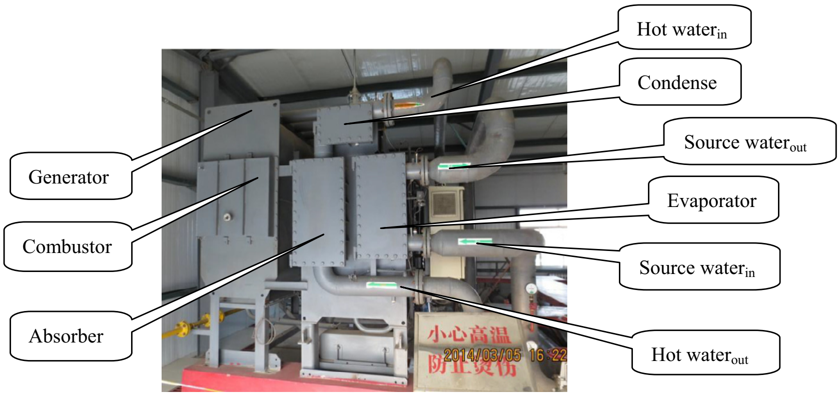


Fig. 24. The type I absorption heat pump installation.

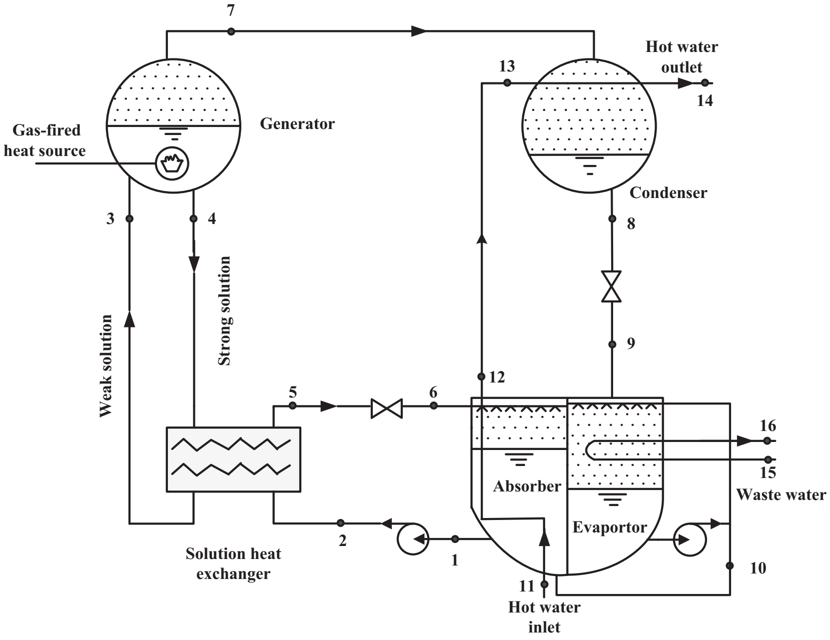


Fig. 25. Schematic diagram of the type I absorption heat pump system used in Lusheng gathering station.

heating for the entire factory area in winter. The gas used as the driving heat source is a byproduct obtained in the oil field and its cost is low. The transformed system can save 60 t of vapor per day when compared with the original heating system, which consisted of the heating furnace and heat exchangers. Because of the limitation on the length of this paper, the COP and exergy analysis cannot be conducted for all the types of heat pumps, but are conducted here for the absorption heat pump as an example.

5.2.1. Mass and energy balance for the LiBr–H_2O absorption heat pump system

The mass balance for the overall system is as follows.

$$m_w = m_s + m_r \tag{2}$$

$$m_s x_s = m_w x_w \tag{3}$$

The energy balance for each component of the absorption heat pump as follows.

$$\sum Q_o - \sum Q_i = \sum (mh)_o - \sum (mh)_i + W \tag{4}$$

The energy balance for the overall system is given by

$$Q_G + Q_E = Q_A + Q_C \tag{5}$$

The COP of the absorption heat pump is defined as follows.

$$COP = (Q_C + Q_A)/Q_G \tag{6}$$

The specific data will be presented in the next section.

5.2.2. Exergy analysis of the LiBr–H_2O absorption heat pump system

Exergy is defined as the amount of work available from an energy source. The maximum amount of work is obtainable when matter and/or energy such as thermal energy is brought to a state of thermodynamic equilibrium with the common components in the environment in which this process takes place with the dead state by means of a reversible process [128]. When the temperature of the environment is T_0, the exergy of a fluid stream is defined as [129]

$$e = h - h_0 - T_0(s - s_0) \tag{7}$$

where e is the exergy of the fluid stream at temperature T; h_0 and s_0 are the enthalpy and entropy, respectively, of the fluid at the ambient temperature T_0, which is taken as 298.15 K in this study.

The exergy loss in each component of the absorption heat pump can be expressed as [129]

$$\Delta E = \sum (me)_i - \sum (me)_o + \left[\sum Q\left(1-\frac{T_0}{T}\right)_i - \sum Q\left(1-\frac{T_0}{T}\right)_o\right] + \sum W \tag{8}$$

where ΔE is the exergy lost or the irreversibility that occurs in the process. The first two terms on the right-hand side are the exergies of the inlet and outlet streams of the control volume. The third and fourth terms are the exergies associated with the heat transferred from the source maintained at temperature T. The last term is the exergy of the mechanical work added to the control volume, and is often negligible for absorption systems, because solution and refrigerant pumps have a low power input.

The total exergy loss in the absorption heat pump system is the sum of the exergy loss in each component, and is given by

$$\Delta E_T = \Delta E_A + \Delta E_G + \Delta E_E + \Delta E_C + \Delta E_{SHX} \tag{9}$$

The exergetic efficiency of the absorption heat pump is given by the following equation [130,131].

$$\eta_e = \frac{\text{exergy of the product}}{\text{exergy of fuel}} = Q_A(1-(T_0/T_A)) + Q_C(1-(T_0/T_C))/Q_G(1-(T_0/T_G)) \tag{10}$$

The thermodynamic parameters of the state, which corresponds to the state points of Fig. 25 are calculated by the actual operation parameters, and are presented in Table 7. With the parameters listed in Table 7, the exergy loss in each component and in the system are calculated, and the results are presented in Table 8. The work input to the solution pumps is neglected.

The exergy loss is used to measure the amount of availability consumed in the process. As seen in Table 8, the absorber has the highest exergy loss, followed closely by the generator, while the exergy losses in the evaporator and condenser are relatively low. The absorber is the worst component from the viewpoint of exergy loss; therefore, more effort needs to be devoted to the improvement of the absorber and other components of the absorption heat pump system.

A computer program, written in Fortran 90, was developed for the performance analysis of the absorption heat pump, based on the first and second laws of thermodynamics. The initial parameters include the mass flow rates of the flue gas, hot water, and waste water; the inlet temperature of the flue gas and hot water; the outlet temperature of the waste water; the heat exchanger effectiveness, and the solution circulation ratio. The thermodynamic properties of the Li–Br solution such as enthalpy, temperature, vapor pressure, and concentration are obtained from the Ref. [132], and the thermodynamic properties of water and steam are obtained from IAPWS-IF 97 [133]. With the given parameters, the program calculates the values of temperature, mass flow rate, concentration, and enthalpy at all the state points of the cycle. Using the program, the COP and exergetic efficiency of the system were calculated at different inlet temperatures of the waste water and hot water.

Table 8
Exergy losses of the absorption heat pump.

Component		Exergy (kW)
Absorber	ΔE_A	13.4
Generator	ΔE_G	10.43
Condenser	ΔE_C	1.07
Evaporator	ΔE_E	0.13
Solution heat exchanger	ΔE_{SHX}	10.29
Whole system	ΔE_T	35.32

Fig. 26 illustrates the effect of inlet temperature of the waste water on the COP and exergetic efficiency of the absorption heat pump. It can be observed that both COP and exergetic efficiency of the system increase with the increase in the waste water inlet temperature. This is because the absorption heat pump system can absorb more heat from the waste water with a higher temperature than from one with a low temperature.

The effect of the inlet temperature of the hot water on the COP and exergetic efficiency of the absorption heat pump system is depicted in Fig. 27. As can be seen from the figure, an increase in the inlet temperature causes a slight decrease in the COP, while the exergetic efficiency remains almost constant.

In terms of the effect on the COP and exergetic efficiency of the absorption heat pump system, the inlet temperature of the waste water has more influence than the inlet temperature of the hot water. The COP and exergetic efficiency have similar behaviors as the inlet temperature of the waste water increases, which implies that the conclusions drawn by the first and second laws of thermodynamics are in good agreement.

5.3. Application in printing and dyeing industry

Printing and dyeing industries involve high energy consumption, high water consumption, and high pollution. A large amount of heat is needed in the production process of printing and dyeing, so a large amount of coal, vapor, and electricity are consumed for

Table 7
The thermodynamic parameters of the state points in absorption heat pump.

State point	P (kPa)	T (°C)	X (%)	h (kJ kg^{-1})	s (kJ kg^{-1} K^{-1})	m (kg s^{-1})
1	5.81	73.2	58.6	174.0463	0.4317	3.4983
2	65.33	73.2	58.6	174.0463	0.4317	3.4983
3	65.33	129	58.6	284.02	0.7271	3.4983
4	65.33	148.7	62.8	333.2703	0.7704	3.2643
5	65.33	85.1	62.8	215.414	0.4644	3.2643
6	5.81	85.1	62.8	215.414	0.4644	3.2643
7	65.33	148.7	0	2776.556	7.8097	0.234
8	65.33	87.9	0	376.5768	1.1779	0.234
9	5.81	34.9	0	376.5768	1.2493	0.234
10	5.81	34.9	0	2564.368	8.3532	0.234
11	–	67.6	–	286.8671	0.9241	14.8
12	–	78.3	–	333.79	1.0524	14.8
13	–	78.3	–	333.79	10.524	14.8
14	–	86.4	–	369.8321	1.1474	14.8
15	–	38.8	–	163.5553	0.5539	41.67
16	–	35.9	–	151.2893	0.4934	41.67
COP = 1.69				η = 63.6%		

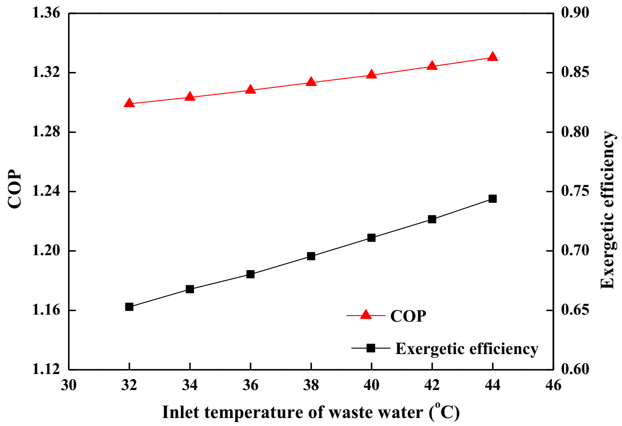


Fig. 26. Effect of inlet temperature of waste water on the COP and exergetic efficiency.

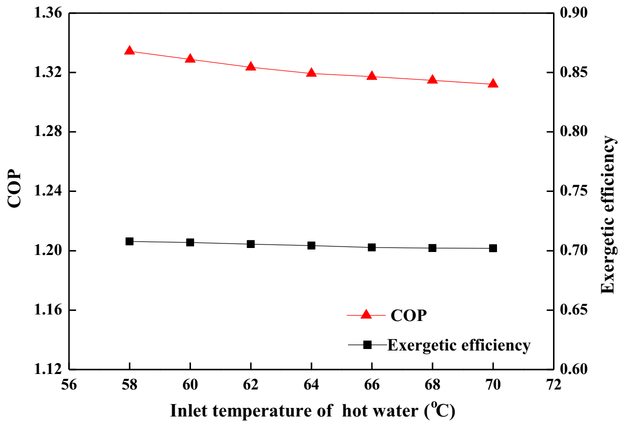


Fig. 27. Effect of inlet temperature of hot water on the COP and exergetic efficiency.

various processes. A large quantity of high temperature wastewater is discharged during the process of scouring, bleaching, dyeing, and washing; and high-temperature exhaust gas is discharged during the process of drying and setting. In the different stages of printing and dyeing, the waste water is discharged at different temperature levels, and the highest temperature that can be reached is 130 °C. During the heat setting process, high temperature vapor is required to finish hot setting, and the temperature of the exhaust gas can be as high as 160–200 °C. If the high temperature wastewater is directly discharged to the sewage plant, the exorbitant waste water temperature would kill the biochemical bacteria and damage the biochemical processing program, which can cause serious thermal pollution and energy wastage [134]. Therefore, it is very important to reform the traditional printing and dyeing industry in China, so that the waste heat of the exhaust gas and waste water can be recovered to provide useful heat in the printing and dyeing process. Further, as an efficient waste heat recovery technology, the industrial heat pump can be applied in the printing and dyeing industry. The printing and dyeing factories are widely distributed along the coast of China, especially in Jiangsu and Zhejiang provinces. The examples presented in this section are taken from these areas.

A dyehouse in Changzhou, Jiangsu Province applies a heat pump to recover the waste heat of the waste water from the printing and dyeing process, and the heat is used to preheat water in the front side of the dye vats. The temperature of the water is increased from 15 °C to 50 °C by the heat pump. The increased temperature can also meet the requirement of space heating in the factory area. Compared with the traditional dyeing process, the heat pump system can save 605,093 t of vapor every year, which is equivalent to saving 715.31 t of standard coal. The factory had recovered the investment cost within two years of operation [104].

Wu et al. [26] designed a capacity-regulated high-temperature heat pump (HTHP) system using a twin-screw compressor to recover waste heat in the dyeing industry, and the performance of the heat pump in a skein-dyeing factory was investigated. In this system, three tanks are used for water storage, and two of them are used for storing waste water discharged from different processes: one is for the high temperature (90 °C), and the other is for the lower temperature (60–80 °C). First, the heat pump absorbs heat from the low-temperature water tank and heats the dyeing liquid to 60 °C, and the dyeing liquid is kept at 60 °C for 10 min. After the thermal insulation process, the dyeing liquid is still heated by the heat pump. When the dyeing liquid temperature increases, the pressure ratio of the twin-screw compressor increases, which may cause serious undercompression. To avoid this problem, the heat pump absorbs heat from the high temperature tank and not from the low temperature tank, when the liquid level in the low temperature tank drops to the safe level, and then the dyeing liquid is heated continuously to 95 °C. In the operation of this heat pump system, heat capacity can be adjusted to control the dyeing liquid temperature to meet the requirement of temperature rising rate in the dyeing heating process. The system performance during the dyeing process is proved to be good with an average COP of 4.2. The operating cost by using this heat pump system is only 53% of that using the traditional dyeing process, and the payback period is 1.84 years.

To estimate the payback period, a dyehouse in Shaoxing, Zhejiang province is taken as an example. This dyehouse discharges waste water at 45 °C at the rate of approximately 2000 t/d, and a heat pump system (Fig. 28) is designed to recover the waste heat from the waste water. In this system, the waste water first flows through an anti-corrosion heat exchanger to heat the clear water from 20 °C to 37 °C, and then the heated clear water is used as the heat source for the heat pump; the heat is transferred to the refrigerant in the evaporator. After this process, the temperature of the water in the evaporator decreases to 30 °C from 37 °C; this can be used as water supplement at the front side of the washing cylinders and dye vats. Then, the refrigerant evaporates and is compressed by a compressor, enters the condenser and releases heat. Meanwhile, the water in condenser is heated from 63 °C to 70 °C, and the heated water can be used for the process of washing and dyeing.

In the heat pump system, the flow rate of hot water is 1700 t/d in the condenser, and the calculated heating capacity is 691 kW. A semi-hermetic twin screw compressor with an input power of 188 kW is employed in the system; the refrigerant is HTR01, and the evaporator and condenser are shell and tube heat exchangers, respectively. The COP of the heat pump is estimated to be 3.7.

Compared with the steam heating system, the heat pump system can save 0.4646 million RMB per year (350 days). An estimation of the total investment of the heat pump system is 0.7 million RMB, so the static payback period is 1.5 years, which is calculated from the ratio of the total investment to the annual savings.

Using heat pump system not only decreases the production cost of an enterprise, but also avoids the burning of coal. Thus, both the benefits of energy saving and environmental protection can be obtained.

In this section, five typical application examples of the usage of industrial heat pumps in different engineering fields are discussed in detail, and some quantitative computations are performed for three examples. The industrial heat pumps can be widely used in

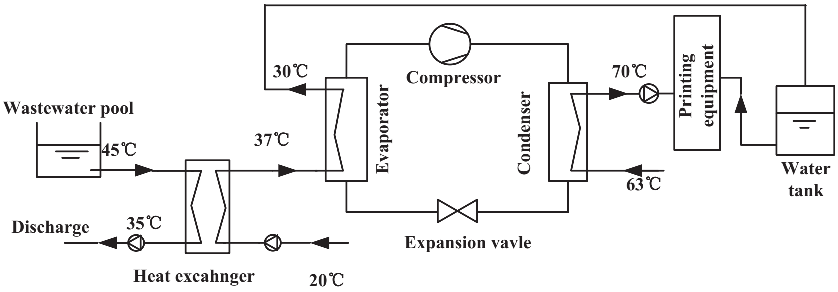


Fig. 28. Schematic diagram of the printing and dyeing waste heat recovery heat pump system.

industrial processes as well as in daily life. A local government department in China is considering the replacement of fossil fuel boiler with electric boiler to offer domestic hot water for heating systems in the center of a big city, for reducing pollution. Though the target of environmental protection can be achieved by using an electric boiler, it is unreasonable from the viewpoint of thermodynamics. Applying heat pumps to produce hot water at 60–70 °C is the best environmental and energy saving method for domestic heating. Taking the district heating program of Oslo as an example, the domestic sewage at 10 °C in the districts in Oslo is used as the heat source for a two-stage heat pump, and finally 90 °C hot water can be obtained [135].

6. Conclusions

Adoption of industrial heat pumps is the approach necessary to efficiently utilize sustainable energy and waste heat in the industrial processes. This can improve the energy utilization efficiency and achieve the goal of greenhouse gas reduction. In this paper, a review of the recent literature on the refrigerants, systems and applications of industrial heat pumps, basically in China, has been presented. The following conclusions can be drawn.

(1) The COPs of the multistage cycles and the cycles integrated with additional components (economizer, intercooler, ejector, etc.) are better than those of the conventional cycles.
(2) The COP of the double-effect absorption heat pump is higher than that of the single-stage system.
(3) For the hybrid system, the COP of the solar assisted heat pump can be much higher than that of the conventional system.

Even though much work has been conducted on system design and experimental research of industrial heat pumps, and though they have been applied in some fields, compared with the vast industrial waste heat released through gases and water every day in China, their applications are far from being adequate. To promote the application of industrial heat pumps in various engineering fields, the following research needs are proposed.

(1) Study on high temperature refrigerants: Some industrial processes like petrochemical processes need higher heating temperature (above 100 °C), but refrigerants that are suitable for such high temperature levels and are environmentally friendly are still limited.
(2) Study on systems and components with higher efficiencies: This includes exploring and constructing innovative systems with higher COP, like the multistage heat pump cycle and the hybrid system. In addition, it is imperative to develop reliable and efficient heat exchangers. Especially while recovering waste heat, the impurities and corrosive effect of the exhaust gas and waste water will cause blockage and corrosion of the heat exchangers, which will decrease the heat transfer coefficient and reduce system operation reliability. Developing practical and efficient heat exchangers suitable for exhaust gases with impurities is a very challenging task.
(3) Compared with the other types of industrial heat pumps, studies on the hybrid system and chemical heat pumps in China are still limited, and further research in these areas is necessary.
(4) Reduction in payback time is a very critical issue to persuade factories or enterprises of small or medium size to accept this energy-saving technique. At present, the application field of industrial heat pumps needs to be enlarged. Furthermore, successful cases of industrial applications that have been in operation for a long time in China should be studied, and their experiences and lessons should be shared in the local and nationwide technical conferences or meetings. Policy and fund support from the local government and cooperation with industrial agencies are needed.
(5) There are three criteria in thermodynamics related to the efficiency of an industrial heat pump: enthalpy efficiency, exergy efficiency, and entransy efficiency. For a chemical heat pump, the conclusions are different and even opposite when different criteria are applied. Further studies on their applicability for different industrial heat pumps are needed.

Investigations are needed to solve the problems mentioned above; this will facilitate extensive application of industrial heat pumps and contribute to a low-carbon environment in China and in other developing countries of the world.

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