Research Status and Technical Application of High-temperature Industrial Heat Pump

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Abstract

In this paper, the research progress of 80-160°C high-temperature industrial heat pump circulation system, refrigerant, component configuration, and market application in recent years is reviewed. For different types of circulation systems applied to high-temperature heat pumps in the industrial field, the working principles, design, and operation standards are described in detail. At the same time, explanations and possible solutions are provided for the respective advantages and disadvantages of different types of circular applications in the industrial field, current development trends, and problems that need to be resolved. The cycle includes closed compression cycle (CCC), mechanical vapor recompression cycle (MVR), hot vapor recompression cycle (TVR), absorption cycle, and other cycles. In the face of market applications, the interpretation of refrigerants that meet high-temperature industrial heat pumps is explained, and the selection criteria for selecting refrigerants for high-temperature industrial heat pumps are described in detail, including good thermodynamic properties, environmental protection, commercial availability, safety, etc. Besides, two kinds of artificial refrigerants are introduced, one is HFO, HFC, HCFS and the other is natural refrigerants H_2O, CO_2 and hydrocarbons (R601, R600). Where in the pump to meet the high-temperature industrial applications and prospects of having a class represents the class of HFO R1336mzz (Z) and R1234ze (Z), it is considered as HFC refrigerants R245fa and R365mfc replacement. Further refrigerant R1224yd (Z) and 1233zd (E) due to its excellent thermodynamic properties, also as new low GWP refrigerant temperature industrial heat pumps. And natural refrigerants again H_2 O, CO_2, and hydrocarbons (R601, R600) as the direction of the heat pump working fluid high-temperature industrial effort. Finally, for high-temperature industrial heat pump cycle components, such as a compressor, an expansion valve, heat exchangers, etc. will be described. The description includes the respective advantages and disadvantages of different types of compressors and focuses on the influence factors that account for the main factors in the actual application design. And how the impact factor affects the performance of the compressor. It also includes the common types and advantages and disadvantages of different types of expansion valves and heat exchangers in industrial high-temperature heat pumps, as well as considerations for component selection.

Keywords

High temperature; Industrial heat pump; Closed compression cycle; Compressor; Natural refrigerant.

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1. INTRODUCTION

1.1. Background

With the development of industrialization, the increase in global energy consumption has been accelerated, especially the consumption of non-renewable fossil fuels, which further promotes energy and environmental problems. At present, fossil fuels are the main source of energy, and their exhaustion is a major challenge facing mankind. Figure 1 shows the proportion of global primary energy consumption, of which 85.2% of oil, coal, and natural gas energy consumption are the main energy materials consumed.

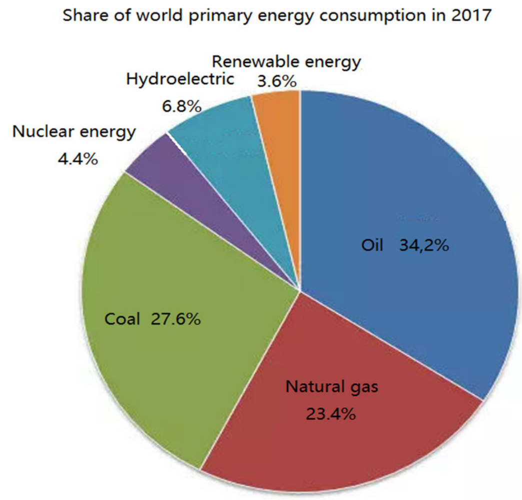

Figure 1. Share of world primary energy consumption in 2017

According to《BP World Energy Statistics Yearbook 2017》published data in Figure 2 shows the energy reserves, calculated oil, coal, and natural gas were available 50.2 years by the 2017 global energy consumption yields 134 years and 50.72 years.

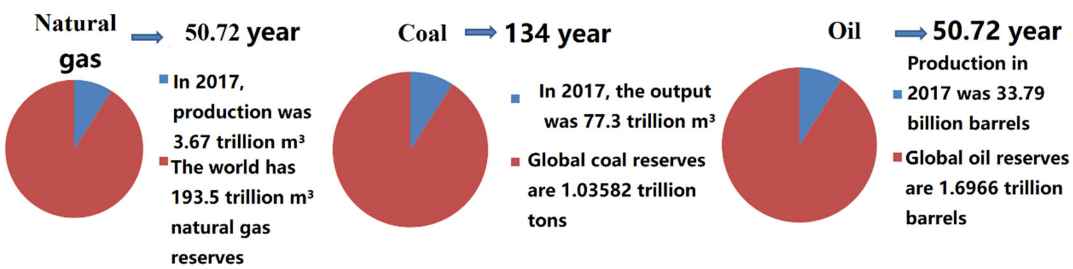

Figure 2. Global fossil energy consumption will take time

Because the heat pump is an attractive energy conversion device, it can provide an effective means of using heat recovery to reduce primary energy consumption, is to solve the energy problems and environmental issues most feasible. A key way to improve the energy efficiency of many industrial activities is to recover every possible waste heat source and convert them into useful output. Furthermore, industrial energy consumption accounts for a large proportion of global energy consumption. In Europe, it accounts for 62% of total energy consumption [1].

2018 China's energy consumption statistics industrial primary energy consumption accounted for 71.1% of the country's total energy consumption [2].

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The application of high-temperature heat pump system in the industrial field has the following significance:

1. First of all, a large amount of industrial waste heat has solved the problem of low-temperature heat source, which can make the heat pump not only make full use of industrial waste heat that is difficult to use by other methods, but also far higher than other heating methods. The efficiency of the heat pump system (the circulation efficiency of the heat pump system is generally about 3) to provide the heat energy required by the industry.

1.2. Application Potential of High-temperature Industrial Heat Pumps

When it comes to the production, processing, and finishing of industrial products, the main demand for heat mainly occurs in the above process. Generally, the starting temperature for high-temperature industrial heat pump applications is above 80°C.

Related to industrial production, processing, and finishing process, the main demand for heat occurs mainly in the above process. Generally, the starting temperature for high-temperature industrial heat pump applications is above 80°C. Figure 3 shows the distribution of industrial heat required by different sectors and temperature ranges in the industrial sector in Europe. Facing the European heat pump market, Nellissen & Wolf used data to analyze the technical heat potential below 150°C, which is about 626 PJ, which can be achieved by heat pumps [3].

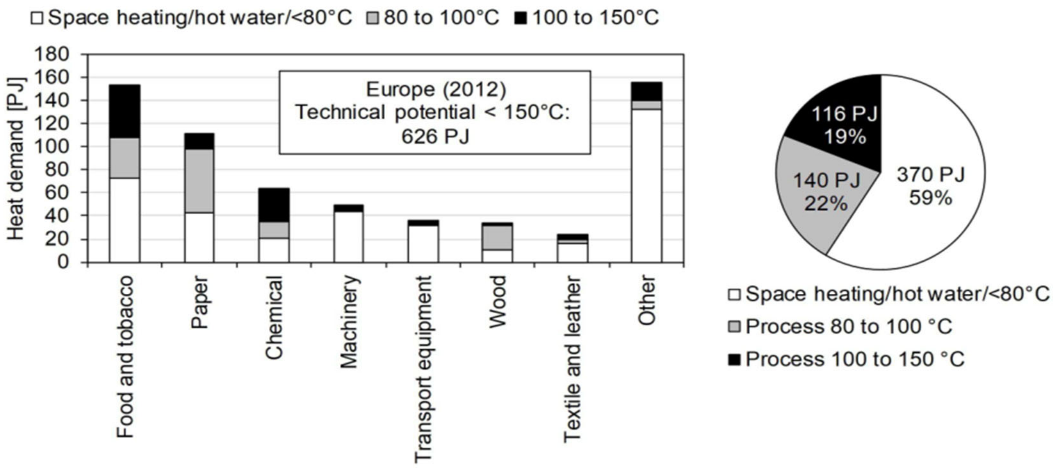

Figure 3. Technical market potential of process heat in Europe, industrial heat pumps distributed by temperature and industrial sub-sectors [3]

Among them, there are about 116 PJ, and 100-150°C accounts for 19%. In this temperature range, high-temperature industrial heat pumps can fully meet the requirements. In the temperature range above 150°C, the vapor compression heat pump technology currently cannot meet actual operational requirements. The main application technology potentials of high-temperature industrial heat pumps in the temperature range of 100-150°C are in the chemical, paper, and food and tobacco industries (the black shaded bar on the left in the figure). In Europe, the theoretical market potential of process heat in the industrial sector will be greater, but due to practical limitations, it is usually not fully developed. In general, high-temperature industrial heat pumps have huge application potential in evaporation, distillation, pasteurization, sterilization, and drying processes.

Fox et al. [4] investigated the industrial energy consumption in the United States in 2008, when a large amount of process steam below 260°C was used. As shown in Figure 1.5, the total process heat demand in the temperature range of 40-200°C is 3416 PJ. Industries such as papermaking, pulping, chemicals, food, and metals are identified as the main process heat

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potential, and these industries are also consistent with the main consumer sectors of natural gas. All industrial sub-sectors use steam in a temperature range suitable for high-temperature industrial heat pump applications.

1.3. Domestic and Foreign High-temperature Industrial Heat Pump Projects

Domestically, in early 1955 heat pump pioneers in Tianjin University Lvcan Ren proposed the need for heat pump applications, it was not until the early 2000s, they began to slowly emerge a study on the energy efficiency of residential heat pumps. Up to now, the residential heat pump technology has completed great development and application, which can meet the heating needs of some residents in China [5]. However, on the other hand, domestic research and application of high-temperature industrial heat pumps for heat pump recovery of low-grade waste heat are relatively rare. In recent years, with the implementation of the government's policy on energy conservation and emission reduction, the use of industrial heat pump technology to recover industrial waste heat has gradually made significant progress in China [6-9].

In foreign countries, in 2010, the International Energy Agency (IEA) launched a new project called Annex 21 "Industrial Heat Pump Applications", which focuses on heat pumps for high-temperature industrial and commercial applications [10]. According to the calculation of the annex project content, the establishment of the industrial heat pump application in the annex can reduce the global power generation capacity of 50-150GW, accounting for about 2-5% of the current world's total power generation. At the same time, the global net emission reductions of the projects in the comprehensive assessment annex are as follows:

1. SO_x——295~695 thousand tonners/years;
2. NO_x——180~425 thousand tonners/years;
3. CO ——55~125 thousand tonners/years;
4. CH_4——3~6 thousand tonners/years;
5. $Particulates$——10~24 thousand tonners/years;
6. CO_2——92~215 thousand tonners/years;

2. RESEARCH PROGRESS OF DIFFERENT INDUSTRIAL HEAT PUMP CYCLES

2.1. Introduction

As we all know, the heat pump is described by analogy as a kind of equipment, driven by a certain type of primary energy, the heat rises from a low-temperature level (heat source) to a higher temperature level (radiator). In recent years, as people realize that this equipment is applied to the field of industrial use to play its important role, rational use of industrial waste heat and cold to achieve the function of energy-saving and emission reduction. Generally, heat pump cycles are widely used in industrial applications. These cycles can be divided into the following categories:1. Closed-loop

(1) Closed compression cycle

(2) Absorption cycle

2. Open loop

(1) Mechanical vapor recompression cycle

(2) Hot steam recompression cycle

3. Other cycles

In addition to the above-mentioned cycles, chemical heat pump cycles, hybrid system cycles, and Joule, Stirling, and Peltier cycles are also considered potential industrial heat pumps. However, in the current development trend, these technologies are temporarily not practical in

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industrial applications. Further evaluation of the merits of the heat pump cycle performance, evaluated by a coefficient called the coefficient of performance (COP) of. COP is defined as:

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

Where Q is the useful heat transferred by the radiator, and P is the input energy of the compressor.

2.2. Closed Compression Cycle (CCC)

2.2.1 Standards for operational design

The simplest closed-loop heat pump principle is shown in Figure 4. A simply closed compression cycle usually consists of four components: an evaporator, a compressor, a condenser, and an expansion valve, one compressor. These devices form a closed circuit, and the refrigerant circulates throughout the cycle.

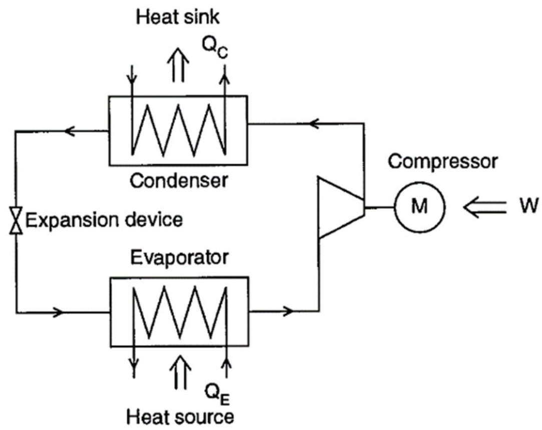

Figure 4. The simply closed compression cycle

Figure 5 shows the principle of the cycle and the corresponding pressure enthalpy diagram. The working fluid evaporates and absorbs heat in the evaporator (state point 1), and then flows into the compressor in the state of superheated steam (state point 2), and then becomes high-pressure superheated steam into the condenser after the compressor works. The heat is released in the condenser, the working fluid is condensed into a liquid state (state point 3), and then the liquid working fluid passes through the expansion valve (state point 4) and returns to the evaporator, thus completing a complete closed cycle. In this process, the low-temperature heat source transfers energy to the high-temperature medium that exchanges heat with the condenser through this cycle, so that the higher temperature and high temperature produced can be used for the process heat required in various industrial processes.

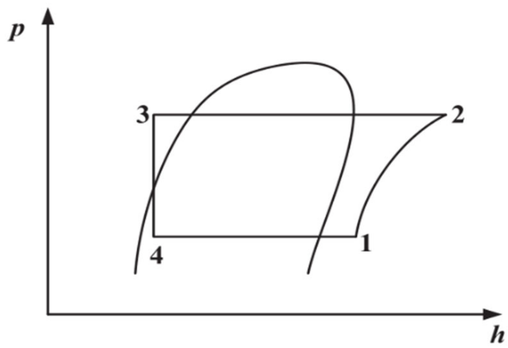

Figure 5. Pressure-enthalpy diagram for a thermodynamic cycle

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In an industrial heat pump, if the radiator has a sensible heat flow, which causes a temperature change during heating, the method shown in Figure 6 can be used to add a supercooled to the condensate after passing through the condenser to perform a subcooling cycle. This means that without additional compressor work, the heat transferred by the condenser has increased, that is, the COP and capacity of the cycle have increased. But at the same time, this also increases the cost of the equipment investment of the subcooled. Evaluating whether to add a supercooled should be based on actual conditions, and comprehensively consider the economic cost and the effectiveness of the resulting COP improvement. When the radiator is liquid, the design of the subcooling cycle is suitable and economical. On average, the COP and capacity increase by about 1% for every 1°C increase in subcooling.

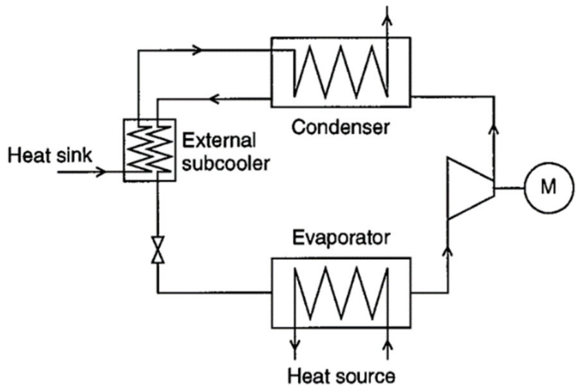

Figure 6. Simply closed compression cycle and subcooled

Theoretically, the state before the working fluid enters the compressor can be dry, saturated steam. But in most cases, a hard condition of the working fluid before entering the compressor must meet the superheat of 5-10°C. The purpose of this is to prevent small droplets from entering the compressor.

2.2.2 Multi-stage circulation

When the temperature of the radiator is much higher than the temperature of the heat source, a multi-stage circulation system is recommended. The multi-stage vapor compression system can be divided into a composite system and a cascade system [11].

The multi-stage circulation system has at least one high-pressure compressor and one low-pressure compressor. At different stages of compression, it is possible to try to use different working fluids to achieve an optimal pressure ratio. Unlike single-stage systems, multi-stage systems have smaller compression ratios, higher efficiency per stage, better cooling, lower exhaust temperatures for advanced compressors, and greater flexibility [12-13]. In a multistage system, the pressure between the exhaust pressure of the higher compressor and the suction pressure of the lower compressor is called the interstage pressure. Usually, the inter-stage pressure of the two-stage system is determined first so that the compression ratio between the two stages is almost equal, to achieve a higher coefficient of performance (COP) [13]. In cold areas of Japan, Tanaka and Kotoh studied and analyzed the performance of a two-stage compressor heat pump water heater using CO_2 as the working fluid [14]. They noted that the ratio of the intake pressure (low pressure) to the discharge pressure (high pressure) of the compressor is large under harsh operating conditions in cold regions with minimum temperatures of -10 to -20°C. This only leads directly to a decrease in water heating capacity and system COP. To improve the performance and reliability of their high-pressure system, they not only divided the compression stroke into two stages but also allowed the refrigerant to be injected at an intermediate pressure. Therefore, in extremely cold conditions, the composite multistage high-pressure system is the best choice to improve the system COP. The cascaded

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system consists of two single-stage cooling systems that operate independently: a lower system that maintains a lower evaporation temperature and produces cooling effects, and a higher system that operates at a higher evaporation temperature. The two independent systems are connected by a cascade system, in which the heat released by the condenser circulating in the lower level compressor is absorbed by the evaporator circulating in the higher level compressor.

In terms of closed compression cycles, the contributions of researchers can be summarized as follows.

(1) To achieve the purpose of improving the COP and energy efficiency of the system, some new equipment has been added to the traditional vapor compression system, such as sub-cooler, economizer reheaters, and intermediate heat exchangers.

(2) To meet the industrial demand for high-temperature heat, some new systems have been proposed based on the vapor compression system. Including new systems such as composite systems and cascade systems. The performance of the new heat pump system is studied, which provides a reference for the design and optimization of the new heat pump system.

2.3. Mechanical Vapor Recompression Cycle (MVR)

Vapor compression is a technology, a technology that can be repeatedly applied, and a technology that can increase the pressure and temperature of the waste heat of exhaust gas. Generally, it is called mechanical vapor recompression or MVR heat pump. There are several types of vapor compression systems. There are several types of vapor compression systems. The most common type of MVR system is the direct compression of process steam. After compression, the steam is condensed in a heat exchanger to meet the heat demand. The second semi-open MVR system is exactly the opposite of the previous type of configuration. This system has only one evaporator, but not a condenser. This special MVR system can be used in the process flow required for gasification at a higher temperature. The heat source can be contaminated steam or other liquids.

In each design, it is important to carefully analyze the balance between operating costs and investment costs. The comparison between the direct semi-open mechanical vapor recompression cycle (MVR) system and the closed compression cycle (CCC) indirect system shows:

(1) From the point of view of thermodynamics and economics, the MVR direct system is more preferable. In the industrial process, the CCC indirect system is more flexible than the direct system, but it is more capital-intensive. Indirect systems are more advantageous for processes with contaminated fluids and can be more easily combined with certain types of processes (such as batch processes). The indirect system also means that the compressor can be more protected if it encounters a compressor interruption when it is running.

(2) In the case of low heat source temperature, the biggest drawback of MVR technology is the relatively large amount of steam, which means there is a risk of air leakage. Therefore, if the purpose of production is low-pressure steam, this technology is rarely used when the heat source temperature is lower than about 80°C. However, if the temperature rise is small (less than about 20°C), lower values tend to appear.

2.4. Thermal Vapour Recompression (TVR)

The ejector is an indispensable component in refrigeration and air conditioning, desalination, petroleum refining, chemical, and other industries [15]. Besides, the ejector is an integral part of the distillation column, condenser, and other heat exchange processes.

The biggest difference between this type of heat pump and the mechanical vapor compressor is that it is driven by heat (that is, steam) instead of electricity. It is also called a jet heat pump.

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Such a heat pump has a simple design structure and does not contain any other moving parts. On the other hand, it requires higher pressure power steam, most of which is 7-15bar. It can be applied to industry, designed to meet the heat load of different requirements of different processes. In real life, the common application of the TVR system is distillation and evaporation, which can raise the temperature by 10-20°C. The important advantages of this cycle are a simple design, low capital costs, and corresponding low maintenance costs. On the other hand, the noise level of such devices can be quite high. Using the data provided by a French manufacturer (Entropy), the COP value of the dual ejector device under different conditions was calculated. An important ejector pump system was recently developed. The jet compression heat pump uses low-temperature heat energy to provide space cooling and heating [16-18].

3. REFRIGERANT

3.1. Selection of Refrigerant

Related to the design of a high-temperature industrial heat pump system, the first to face the first choice of the heat pump cycle system working fluid. Only by selecting the appropriate circulating working fluid, the heat pump system can meet the requirements of the set working conditions. At present, there are more than 5 million kinds of organic substances and more than 50,000 kinds of inorganic substances, but not many of them are suitable for high-temperature industrial heat pump cycles. When selecting working fluids, the main factors to be considered are as follows:

(1) Suitable condensing pressure;

(2) Appropriate evaporation pressure to avoid negative pressure in the system;

(3) Appropriate volumetric heating capacity, so as not to make the compressor too large and increase the cost of equipment;

(4) Other common requirements as a circulating working fluid, such as none, little harm to the environment, stable chemical properties, excellent thermal properties, etc.;

(5) Pursuing a higher cycle performance coefficient under the premise of meeting the above requirements.

It is also worth noting that the maximum operating temperature of the heat pump cycle under subcritical conditions is determined by the critical temperature of the refrigerant. At the same time, the critical temperature of the refrigerant must be maintained at a certain temperature difference from the required condensation temperature, generally between 10-15°C, for example. The purpose of this is to ensure the efficient operation of the subcritical heat pump. On the one hand, the closer the condensation temperature is to the critical point, the smaller the condensation enthalpy, and the smaller the heating coefficient. The pressure level of the high-temperature industrial heat pump system should be kept below the practical limit of about 30 bar because of the limit level that the existing heat pump equipment can support. But there are exceptions. Compressors running R32 and R410A refrigerants are sufficient to withstand pressures up to 50bar.

On the other hand, to minimize the compressor power, the pressure ratio should be as low as possible. It is necessary to select the appropriate oil to ensure the sealing, lubricity, and temperature stability of the heat pump. At the current level of technological development, the compression end temperature (for example, the temperature of the piston head) should not exceed about 150°C. Because too high compressor discharge temperature may cause damage to the inside of the compressor, it will also cause the lubricating oil to lose lubrication. What's more, it leads to the chemical decomposition and coking of the oil. Also, the working fluid must be chemically compatible with metal materials such as aluminum, steel, copper, and polymers.

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3.2. Research Progress at Home and Abroad

The most commonly used high-temperature industrial heat pump is the vapor compression cycle and the refrigerants R22 and R114 that are commonly used in vapor compression cycles on the market, so current research focuses on finding a substitute for the former. The other two common high-critical temperatures R365mfc and R245f are also the replacement roles of high-temperature industrial heat pumps for refrigerants with high condensing temperatures. The biggest difference between industrial heat pumps and traditional vapor compression cycle heat pumps is that the heating temperature used is quite high, generally above 80°C; therefore, finding suitable high-temperature refrigerants is one of the current research focuses on industrial heat pumps. This article discusses two types of refrigerants:

(1) Artificial refrigerants, such as hydro fluoro olefins (HFO), hydrochlorofluorocarbons (HFC), and hydrochlorofluorocarbons and their mixtures (HFCs).

(2) Natural refrigerants, such as CO_2, NH_3 and hydrocarbons;

The requirements for refrigerants are high critical temperature, low-pressure range, no ozone depletion potential (ODP), low global warming potential (GWP), non-combustion, and non-toxic. Although, so far the refrigerant that meets all the above requirements has not been found by researchers yet such an ideal refrigerant. However, with the joint efforts of researchers from all over the world, meeting certain requirements can be achieved by some refrigerants.

In the future, the high-condensing temperature HFC refrigerants R245fa and R365mfc are most likely to be replaced by HFO refrigeration R1336mzz (Z) and R1234ze (Z) for environmental protection and thermal properties. The operating pressure upper limit of R1336mmz(Z) is 29.0 bar, and the critical temperature is as high as 171.3°C, which is its most prominent advantage. Besides, its safety level is A1, GWP is 2, ODP is 0, and its atmospheric lifetime is 22 days [19]. Chemours is about to commercialize R1336mzz(Z), which can provide high-temperature temperatures exceeding 160°C. If the refrigerant is used in organic Rankine cycle, steam generation, and waste heat recovery applications, its temperature can even be stabilized to 250°C [20]. Indoor experiments show that the compatibility of this material with copper and steel is similar to that of R245fa. If the system chooses lubricants, it is recommended to use high-viscosity polyol ester oil (POE) because it is completely miscible in a wide range of temperature and composition.

Refrigerant R1234ze(Z), whose critical temperature and pressure are 150.1°C and 35.3 bar respectively, allows subcritical cycle operation at high temperature, its flammability grade is A2L, and GWP is less than 1[21-22]. Longo et al. [23] tested the pressure drop and heat transfer coefficient of R1234ze(Z) steam when condensed in the heat exchanger. Compared with the results of R236fa, R134a, R600a, and R1234ze(E), they found that R1234ze(Z) The heat transfer coefficient is the highest. Brown et al. [24] also found that R1234ze(Z) can be used as a substitute for R114 in high-temperature heat pumps. Fukuda et al. [25] conducted a thermodynamic evaluation on R1234ze(E) and R1234ze(Z) and believed that R1234ze(Z) is more suitable for high-temperature heat pump systems for industrial applications. Therefore, in high-temperature industrial heat pump applications, R1234ze(Z) is considered a suitable substitute for R114.

Suitable natural refrigerants for high-temperature applications include $\mathbf{H_2O}$, $\mathbf{CO_2}$ and hydrocarbons (R601, R600). The huge latent heat makes water above 150°C have an attractive attraction that cannot be ignored. Most of the heat pump cycle using water as the working fluid is below atmospheric pressure. Due to the low water vapor density, the required heat transfer area and pressure ratio are very high. Usually, large compressors or high-flow high-speed oil-free turbocompressors are used. To keep the discharge temperature at a controllable level, several water vapor recompression stages need to be carried out under the condition of inter cooling [26]. If the inlet temperature of the radiator does not exceed the critical temperature

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(31°C, 73.6 bar), then CO_2 is suitable as a high temperature and high-pressure fluid. In this transcritical or supercritical process, the heat transferred to the radiator has a large temperature slip in the gas cooler, which makes R744 particularly suitable for processes that require large temperature slips, such as hot water heating.

Domestically, in the field of colleges and universities, Zhu et al. of Tsinghua University [43] developed a kind of R124/R142b/R600a ternary mixture HTR01. The experimental test results show that the outlet temperature of the condenser can reach 90°C, and the COP is above 3. Then, they developed HTR02, HTR03, and HTR04 refrigerant mixtures and tested their thermal performance through experiments. After HTR03 and HTR04 are charged in the R134a compressor, the heat pump can stably produce hot water with a temperature above 85°C. HTR01 and HTR02 have been used as working fluids for high-temperature heat pumps in various industrial processes in China [44].

4. OVERVIEW OF HIGH-TEMPERATURE INDUSTRIAL HEAT PUMP COMPONENT CONFIGURATION AND MARKET APPLICATION

4.1. Heat Pump Components

4.1.1 Compressor

In general, in the selection of components, the choice of a compressor affects the quality of the entire system to a certain extent, which is a core design issue. The widely used cycles in high-temperature industrial heat pumps are vapor compression cycles and mechanical vapor recompression cycles. This section mainly introduces the compressors of these two types of cycles.

The three traditional compressors commonly used in vapor compression cycle components are reciprocating compressors, (twin) screw compressors, and centrifugal compressors. Reciprocating compressors are often used in small and medium-sized systems, screw compressors are used in medium-sized systems, and centrifugal compressors are often used in large-scale systems. Reciprocating and screw compressors require lubricants to reduce friction and maintain the normal operation. The centrifugal compressor does not need lubricant during normal operation. Furthermore, the screw compressor mixes a large amount of oil in the working fluid to maintain the seal and cooling inside the compressor.

In the mechanical vapor recompression cycle (MVR) they are usually divided into two categories:

(1) Pneumatic or turbocharged compressor

(2) Positive displacement or positive displacement compressor

As shown in Figure 7, it is expressed as the classification of MVR compressors.

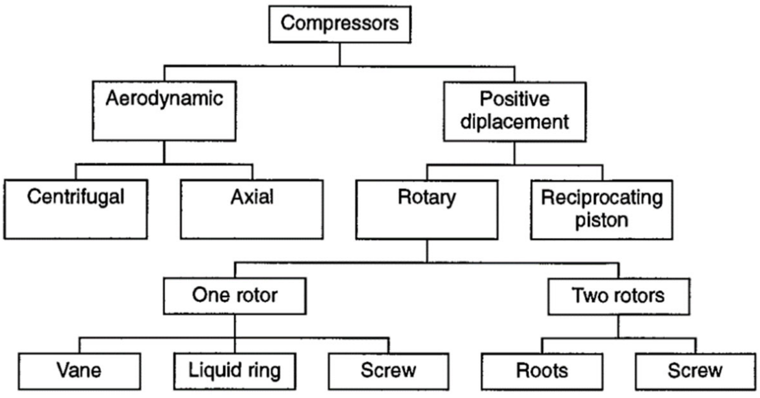

Figure 7. Classification of mechanical compressors

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Axial turbo compressors: Axial compressors are very compact, which means that they will have a very large capacity in the body with a small structure. They are also more efficient than positive displacement compressors and generally higher than radial turbo compressors. Axial turbo compressors maintain high efficiency due to their good sealing properties. But its capacity control is relatively difficult. It is also very sensitive to droplets, as this can lead to blade erosion and failure. Radial turbo compressor: The radial turbo compressor is the most common type of compressor in the MVR device, also known as a centrifugal compressor. Each time the further completion of the pressure boost is completed, it is proportional to the square of the rotational speed of the impeller. Therefore, the pressure ratio of each stage of the vapor compression compressor can exceed 3 times. The impeller speed usually does not exceed 450 m/s. For compressors of standard materials, the pressure ratio of each stage is limited to about 2. When the carburetor is compressed, the increase in pressure also means high temperature, cooling the working fluid to extend the life of the compressor and reduce the compression workload.

The capacity of the centrifugal compressor can be controlled while maintaining high efficiency, with inlet guide vanes, adjustable diffusion vanes, or variable speed. In a multi-stage installation, cooling can be done either through liquid injection or indirectly through heat exchange between steam. These control methods are also used to avoid unstable operations. To avoid corrosion caused by liquid droplets, centrifugal compressors are usually equipped with a liquid separator in the suction line.

Screw compressors are common in refrigeration and heat pump installations and are used to compress halogenated hydrocarbons and ammonia. In these applications, the compressor is usually oil-immersed. However, oil-free compressors must be used for vapor compression. The cooling in the compressor can be accomplished by water injection or water cooling of compressor components. Sealing and lubrication can be accomplished by injecting water to create a liquid film, or by coating a special coating on the rotor to obtain a satisfactory internal seal. Water injection can be done through the water inlet or the economizer.

Reciprocating compressors are rarely used for vapor compression, mainly because oil-free reciprocating compressors are very expensive. They are also very sensitive to the liquid in the compressor.

Roots Blowers is a powerful and cheap compressor. In order not to make the leakage too large, the pressure difference between each compressor is limited to approximately 1 bar. Its isentropic efficiency is lower than other types of steam compressors, generally between 45% and 55%. Currently, under development, the price is about half of the traditional turbo compressor, and the isentropic efficiency is expected to reach 55-65%.

Ring compressors are rarely used in MVR applications. Their simple design makes them relatively cheap. They can also work with heavily polluted steam. This type of compressor has three disadvantages: low capacity, pressure ratio can only reach about 1.5, and low isentropic efficiency (20-50%).

4.1.2 Heat exchanger and expansion valve

The common settings of the heat exchanger follow the economical best and minimum temperature difference, and the specific design varies according to the actual application. Generally, when the radiator and the heat source are liquid, the temperature difference of the evaporator is controlled at 4-8°C, and that of the condenser is controlled at 2-6°C. But if the radiator and the heat source are in the gas phase, the temperature difference will be higher. The evaporator is usually designed to have a pressure drop of approximately 2°C at the evaporating temperature. In the condenser, the pressure drop is usually equivalent to 1-2°C.

There are many types of expansion valves. For example, thermostatic valve, static pressure valve, and electric control valve. Electronic control valves are generally used in industrial plants.

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Because the operation of the electronic control valve is more reliable than others, it also ensures that the overheating after the evaporator is kept at a reasonable level. For reciprocating and turbo compressors, the most important thing is that the vapor of the evaporator must not contain any liquid droplets, because liquid droplets can cause corrosion and implosion problems, which will eventually lead to compressor failure. Therefore, it is necessary to ensure that there is sufficient overheating before entering the compressor, which is generally controlled at about 10°C.

4.2. Overview of Market Applications

In recent years, heat pump models and high radiator temperatures on the market have steadily increased. More than 20 heat pump models from 13 manufacturers have been confirmed. Shown in Table 1, shows the relevant product parameters of high-temperature industrial heat pump applications on the market [29-31]. The temperature of the radiator in some companies has exceeded 110°C. What's more, some heat pumps can already provide heat at 130-165°C. The heating capacity of 20KW-20MW has been applied in the market.

Table 1. Application of high-temperature heat pump parameters in the market [29-31]

Manufacturer	Product	Refrigerant	Max. heat sink temperature(°C)	Heating capacity(kw)	Compressor of Type
Kobe Steel	SGH165	R134a/R245fa	165	70-660	Twin screw
	SGH120	R245fa	120	70-370	
	HEM-HR90,-90A	R134a/R245fa	90	70-230	
Viking Heating Engines AS	HeatBooster S4	R1336mzz(Z)R245fa	150	28-188	Piston
Ochsner Energie Technik GmbH	IWWDSS R2R3b	R134a/OKO1	130	170-750	screw
	IWWDS ER3b	OKO(R245fa)	130	170-750	
	IWWHS ER3b	OKO(R245fa)	95	60-850	
Hybrid Energy	Hybrid Heat Pump	R717/R718	120	250-2500	Piston
Mayekawa	Eco Sirocco	R744	120	65-90	screw
	Eco Cute Unimo	R744	90	45-110	
Combitherm	HWW 245fa HWW R1234ze	R245fa R1234ze	120 95	62-252 85-1301	Piston
Durr themea Gmbh	themeco2	R744	90	51-2200	Piston
Friotherm	Unitop22	R1234ze	95	600-3600	Turbo (two-stage)
	Unitop50	R134a	90	9000-20000	
Star Refrigeration	Neatpump	R717	90	350-1500	screw
GEA Refrigeration	GEA Grasso FX P 63bar	R717	90	2000-4500	Twin screw (63bar)
Johnson Controls	HeatPAC HPX	R717	90	326-1324	Piston
	HeatPAC Screw	R717	90	230-1315	Screw
	Titan OM	R134a	90	5000-20000	Turbo
Mitsubishi	ETW-L	R134a	90	340-600	Turbo
Viessmann	Vitocal 350-HT Pro	R1234ze	90	148-390	Piston

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Nevertheless, there are still major limitations in the application of high-temperature industrial heat pumps. Because the use of some refrigerants brings great harm to the environment, given this, some refrigerants have to be phased out despite their good thermophysical properties and effectiveness. It is especially worth noting that Europe has issued laws and regulations that will gradually reduce the use of HFCs such as R134A, R245fa, or R365mfc in 2030.

The most promising for high-temperature industrial heat pumps are HFOs, such as R1336mzz (Z) or R1233zd (E), which have low toxicity, no flame propagation, and low GWP. R1336mzz(Z) will soon be commercialized in Chemours under the Opteon™ brand. Honeywell recommends Solstice®ze (R1234ze(E)) and Solstice®zd (R1233zd) as refrigerants for high-temperature industrial heat pump applications. Although HFO working fluids and natural refrigerants (such as R601, R600) are not restricted by regulations, research on these refrigerants is still scarce.

5. CHALLENGES AND CONCLUSIONS

Although high-temperature industrial heat pumps have good prospects, the following obstacles still exist in the market promotion in industrial applications:

(1) Lack of suitable refrigerants and suitable compressors in the high-temperature range of low GWP;

(2) Incomplete understanding of high-temperature industrial heat pump technology from users to investors to engineering and technical personnel;

(3) Lack of knowledge of integration of high-temperature heat pumps in industrial processes, and can only customize designs, resulting in soaring costs;

(4) Not only is there a lack of a suitable pilot demonstration system, but it is also not economical compared with low-cost fossil fuels.

To sum up, the high-temperature heat pump technology industry accelerates the first major obstacle to market applications, with a good economy while maintaining high efficiency. In most cases, the design of large heat pumps is specially customized according to actual conditions, or products produced in small batches. If you want to change this model, you must develop economies of scale and increase productivity in mass production. The only available method is to modularize the heat pump so that heat pump components or hydraulic integration can be mass-produced, thereby reducing costs and forming scale. Another obstacle is the lack of available compressors and refrigerants.

In the past few years, research work worldwide has begun to increase. However, the implementation of high-temperature heat pump applications in existing factories requires a very high cost and the factory needs to think twice about radiators and heat sources. One way to solve this problem requires the government to formulate policies to promote the demonstration of the successful integration of heat pumps into industrial processes. Second, before the production of factory equipment, reasonable design of factory equipment manufacturers cooperate with reasonable design to directly integrate the heat pump into the production machine and promote the overall equipment in the market. At present, the International Energy Agency (IEA) has launched several solutions for industrial heat pumps. Efforts are being made to overcome the existing difficulties and obstacles and promote industrial heat pumps to enter the market on a larger scale. The use of high-temperature industrial heat pumps is a necessary way to effectively utilize sustainable energy and waste heat in industrial processes. This can improve energy efficiency and achieve the goal of reducing greenhouse gas emissions. This article reviews the research progress of 80-160°C high temperature industrial heat pump cycle system, refrigerant, component configuration, and

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market application at home and abroad in recent years, and the following conclusions can be drawn.

(1) The cop with multi-stage circulation and additional circulation (economizer, intercooler, ejector, etc.) is better than conventional circulation.

(2) The COP of the double-effect absorption heat pump is higher than that of the single-stage system.

(3) To meet the industrial demand for high-temperature heat, some new systems have been proposed based on the vapor compression system. Including new systems such as composite systems and cascade systems. The performance of the new heat pump system is studied, which provides a reference for the design and optimization of the new heat pump system.

(4) The HFC refrigerants R245fa and R365mfc with high condensing temperature are most likely to be replaced by HFO refrigerants R1336mzz (Z) and R1234ze (Z) for environmental protection and thermal properties.

(5) The refrigerants R1336mzz (Z) and R1234ze (Z) include $\mathbf{H_2}$O, $\mathbf{CO_2}$, and hydrocarbons (R601, R600), and commercialized R1233zd (E) and R1224yd (Z) will be the working fluids of high-temperature industrial heat pumps in the future. development trend.

(6) The circulating components of high-temperature industrial heat pumps in the market, such as compressors, heat exchangers, and expansion valves, have also been slowly developed in recent years. The time node for commercialization and mass production of high-temperature industrial heat pump components will be advanced.

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