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Water vapor compression and its various applications

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ABSTRACT

From the view of environment protection, water refrigerant can completely satisfy the requirements of the energy-saving and emission-reduction. Currently, centrifugal, roots and screw compressor are three main kinds of water vapor compressors. Centrifugal water vapor compressor has the advantage of larger volume flow rate, but it has smaller single stage compression ratio, high discharge temperature, droplet sensitivity and severe and expensive blade materials. The largest volume flow rate and smallest compression ratio system is more suitable application field for centrifugal water vapor compressor. Roots water vapor compressor has the advantages of less vibration components and simple structure. However, it also has smaller compression ratio compared with screw water vapor compressor, which results in that it is usually used in the small volume flow rate, medium heating capacity and temperature rise systems. Screw water vapor compressor has the advantages of good stability, larger compression ratio and wet compression; however its volume flow rate is not very large. It is more suitable for the refrigeration system with medium and smaller volume flow rate and larger compression ratio.

The main applications of water vapor compressors can be divided into mechanical vapor recompression (MVR) system, water vapor heat pump system and water vapor refrigeration system. MVR system is a high efficiency and energy saving technology and its advantages lie in the simple process, low operation cost, simple structure and small covered area. Water vapor refrigeration and heat pump systems both face the challenges of evaporation in vacuum, big compression ratio, small volumetric refrigeration capacity, large volume flow rate and high exhaust temperature. Nevertheless, the coefficients of performance (COP) of them are better than the traditional refrigeration and heat pump systems under certain conditions. Some typical applications of water vapor systems with their own special characteristics are also introduced.

1. Introduction

With the rapid development of the world economy and the continuous growing demand for material, the consumption of energy is increasing rapidly and the energy shortage will be a major problem for the development of the world in the future [1]. While the energy consumption is huge, global environmental issues, such as ozone depletion, global warming, glaciers melting and sea levels rising, are also ringing alarm bells [2]. In the face of fossil energy crisis and the global environmental problems, devoting efforts to developing and using new energy and renewable energy, such as shale oil and gas, combustible ice, solar energy, wind energy, hydropower, geothermal energy, biomass energy, et al., can effectively reduce the dependence on fossil fuels and protect the environment [3–5]. At the same time, promoting the new green energy saving technology and reducing the energy consumption in the production and life are also important means to get rid of the energy crisis [6,7]. Therefore, green energy saving technology is the research core and time focus in various fields of social production and development.

In the area of refrigeration, the search for efficient, green, environmentally friendly and easily available refrigerants has become the consensus [8]. And building economical, energy saving, and efficient circulation systems is also being paid attention in industry. In the principle of green and energy conservation, the paper focuses on water vapor systems and related core equipment which have great potential for development in the future. The main contents can be classified as four main parts. First part introduces the characteristics of water refrigerant and its important effect in the development stage of refrigerant. Second part presents the main types of the water vapor compressors in the systems and their respective characteristics and adaption occasions. Third part studies various types of water vapor systems and corresponding present research status. And the last part introduces some typical water vapor systems with water vapor compressors.

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Nomenclature

COP	coefficient of performance
CHCs	aliphatic fluoro-alkanes
CFCs	chloro-fluoro-carbon
GWP	global warming potential
HCs	hydrocarbons
HCFCs	hydro-chloro-fluoro-carbon
HFCs	hydro-fluoro-carbons
HFOs	hydro-fluoro-olefins
ODP	ozone depletion potential
MVR	mechanical vapor recompression
MVC	mechanical vapor compression

2. A brief historical development of refrigerant

2.1. The development of refrigerant

In the past 200 years, because of the different development demands, the requirements of the refrigerant have also been varied in different periods. According to the different requirements of the refrigerant, the development of refrigerant can be divided into four stages, as shown in Table 1[9,10].

Initially, because of the application requirements and the lack of the cognition of refrigerants properties, refrigerants just needed meet the application requirements and no specific requirements were put forward. So the first generation of refrigerants is substance whatever can be used. Then in order to reduce the economic cost of refrigerants and ensure the safety of equipment and staff, new requirements for the safety of refrigerants were put forward. With steering fluoride as the distinct symbol, the second generation, which is high safety, low economic cost and durable, was developed rapidly at that time. However, with the in-depth study of refrigerants properties, researchers found that the second generation of refrigerants has a huge damage to the ozone layer, which causes serious environmental problems. And then new ozone friendly refrigerants are required, which led to the development of the third generation. The destruction of the third generation of refrigerants on the ozone layer is very small and some refrigerants even have no damage. But with the use of the third generation refrigerant, its significant greenhouse effect seriously limits its further development and no greenhouse effect refrigerants are more suitable. At the same time, the higher and more comprehensive requirements were also proposed for the refrigerants, which are economic, safe, durable, green, environment-friendly and easily available. These requirements promoted the research of water, carbon dioxide, ammonia and hydrocarbons in the first generation, which are the representative of the fourth generation natural refrigerants [11–13].

2.2. Advantages and disadvantages of water as refrigerant

In the fourth generation natural refrigerants, the comparison of the parameters of propane, ammonia, water and carbon dioxide is shown in Table 2[10,14].

The analysis of the fourth generation refrigerants' parameters in Table 2 shows that the water refrigerant has its own characteristics. The advantages of water are shown as following.

(1) No pollution to the environment. As a refrigerant, water's ODP = 0 and GWP < 1, which means water has no damage for the ozone layer and its impact of global warming is small. Water is an environment friendly refrigerant and it has no risk of future restrictions.
(2) Easy access to raw materials and low cost. Water is abound in nature, and compared with any other kinds of refrigerants, water is the most accessible and economical refrigerants. Tap water, treated waste water, or coarsely filtered river water can be used directly as make-up water.
(3) Good security. Water is not toxic, flammable, explosive and doesn't have other dangerous properties. No matter the liquid or gaseous leakage occurs, water cause no safety problems and is the safest refrigerant. This also promises that water has no disposal problem after use.
(4) Good stability and durable. The chemical nature of water is very stable and there is no decomposition of water in the long term use.
(5) Large latent heat of vaporization. Compared with propane, ammonia and carbon dioxide, the latent heat of vaporization and unit mass refrigerating capacity of water are large.
(6) System operation safety. Water works with very low pressure differences, reducing safety precautions.
(7) High theoretical coefficient of performance. Compared with CFCs, water has high theoretical performance of coefficient (COP).
(8) The system working with water as a refrigerant can use direct heat exchangers for evaporation and condensation.

In spite of over advantages, using water as refrigerant has its own challenges needed to be overcome. The physical properties of water, such as low molecular weight, large specific volume and high adiabatic index determine the water vapor systems with small differential pressure, large pressure ratio, small unit volume refrigerating capacity, large volume flow rate and high exhaust temperature [15]. Due to the fact that the saturation pressure of water at 100 °C is equal to the atmospheric pressure, the water vapor systems are often at the state of vacuum, which results in the leakage of non-condensable gases. However, these challenges can be overcome by designing and manufacturing special compressors in water vapor systems.

In 1934, water was used as refrigerant by Belmont in an air conditioning system and it was the first time for water to be documented in the refrigeration field as refrigerant. Afterwards, with the discovery and application of freon refrigerant, the volume and weight of the compressor greatly reduced and compression systems with water as a

Table 1
The development of refrigerant.

	The first generation	The second generation	The third generation	The fourth generation
Time	1830–1930	1931–1990s	1991–2010s	2010-?
Purposes	whatever worked	safety and durability	stratospheric ozone protection	global warming mitigation
Representatives	ethers, CO_2, NH_3, $HCOOCH_3$, HCs, Air, H_2O, SO_2, CCl_4, HCCs and others	HCFCs, HFCs, CFCs, NH_3, H_2O	HCFCs, HFCs, CO_2, NH_3, HCs, H_2O	low-GWP HFCs, HFOs, HCs, NH_3, H_2O, CO_2, Air
Safety level	-	A1	A1, A2	-
ODP[a]	-	approx. 1	mostly 0	mostly 0
GWP(100 years)[b]	-	-	most > 1000	most < 1

[a] ODP: ozone depletion potential.
[b] GWP: global warming potential.