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A review of heat pump systems for heating and cooling of buildings in China in the last decade

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ABSTRACT

Heat pump technology fully shows the principle of energy recycling in terms of Heating, Ventilating and Air Conditioning (HVAC). It avoids unipolarity of energy using in the conventional HVAC system. Heat pumps use high-grade energy as a driving energy, recovering and upgrading low-grade energy for avail, like a pump. Because heat source used in HVAC usually is low temperature heat, heat pump systems adopted in HVAC will help improve heating performance coefficient. Therefore, HVAC is one of ideal users of heat pump applications, and thus high-grade energy used in HVAC can be replaced with a large number of low-temperature renewable energy. Through the heat pump technology, natural low-grade energy stored in the soil, water, air or waste heat from variant industries and daily lives, is supplied for building cooling/heating and hot water serving. Therefore, vast applications and developments of heat pump technology are presented in HVAC in China, and some progresses are achieved in the system innovation, experimental research, product development and engineering application, etc. This paper reviews the progress of researches, applications and development in the field of heat pumps for building cooling/heating in China since the 21st century.

1. Introduction

In the 21st century, the development of heat pump system for heating and cooling of buildings in China is very rapid, whose applications have been widespread. Much progress has made in the theory of system innovation, the experimental research, product development and engineering applications, etc. It plays a positive role in building energy efficiency, which not only makes a positive contribution to energy-saving and emission-reduction, but also provides a new view and technical support for building energy efficiency. In recent years, by the encouragement and support from the local government and relevant departments, the heat pump system has entered a booming period. In Beijing, Shenyang, Tianjin, Shandong, Henan, Hubei, Guangdong, Jiangsu and many other cities or provinces, the applications of heat pump system in buildings are drastically popularized [1]. Generally speaking, these projects show that the heat pump system is better than the conventional air-conditioning system in energy-saving and environmental benefit. However, in the fierce market competition, it has also emerged some problems in the technology, design, construction and operation of heat pump system. Therefore, to the healthy development of heat pump technology in China, it is necessary to make the comprehensive investigation on the situation and the effectiveness of the running heat pump system in every area, as well as providing the objective evaluation. In the countries all over the world, it also has repeatedly appeared stagnation of heat pump development and the fall of heat pump markets. China should learn the experiences and lessons about the development of heat pump from other countries, and focus on the possible problems in the development of heat pump technology, in order to avoid emerging similar stagnation problem of heat pump technology during the rapid development in the future in China.

2. Air source heat pump (ASHP) systems

ASHPs have been widely applied worldwide in recent decades due to their significant energy-saving potential. However, when it operates in humidity and cold environments, its outdoor coil surface will be frosted, thus the heating performances are degraded. To solve the problems of frosting and defrosting, and improve its heating performances in cold climate, a vast majority of researches have been conducted in China in recent decade.

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2.1. Frosting & defrosting

For a space heating ASHP unit, when its outdoor coil surface temperature is below both the air dew point temperature and the freezing point of water, frost will form on it. The structure of outdoor coil and outdoor environment meteorological parameters obviously affect the formation of frost. Of the structure of outdoor coil, the type of fin-tube is more important for the formation of frost. Compared to the plane fin-tube, when using split fin-tube, the growth rate of the frost thickness was more significant in the initial frosting stage. With the increase of the air relative humidity, the coefficient of performance of the ASHP unit with split fin-tube evaporator decreased significantly. However, under low air relative humidity conditions, the frosting duration could be effectively prolonged [2]. Yao [3] established a mathematical model for airside heat exchanger of water chiller/heater of ASHP, and analyzed the influence of temperature and relative humidity of outdoor air, and windward speed on frosting growth. The simulation results provided a basis of analyzing the performance of ASHP with frosting and control of defrosting.

Frost on the outdoor coil surface degrades the performances of ASHP unit. Guo [4] experimentally investigated the effect of frost growth and frost morphology on the performance of ASHP unit. The frost growth was divided into three stages according to its morphology. In the first stage, the heating capacity and COP of ASHP unit increased, when they changed slightly. But they dropped apparently in the third stage. When the outdoor air temperature was about 0 °C with various relative humidity, both the frost growth and the drop in the performance of ASHP were highest. Gong [5] analyzed the performance of ASHP under frosting condition. The effect of eight influence factors to the system performances were considered, including the ambient conditions and structures of heat exchanger. And further the relationships between the ratio, the performance parameters and the frost accumulation were discussed.

With the development of frosting mechanism, some researches proposed frost-free ASHP. One way was to dehumidify the air into the outdoor coil [6], the other was adding a solution to the system, which could extract the heat from the environment and then release it to the evaporator. This novel system could operate more efficiently than the conventional ASHP unit in winter [7]. However, the deficiency of these two ways was that it could not use the condenser heat from the process of frosting. To solve this problem, Jiang [8] designed a novel ASHP system to reduce the impact of frosting, and to achieve defrosting timely and efficiently without stopping heating, which is shown in Fig. 1 When the frost accumulated to a certain thickness, the solution spray subsystem started to work and it sprayed the liquid desiccant windward to the fin-tube, which could melt the frost rapidly.

The frost-free of ASHP unit under frosting conditions is crucial for improving its performance and extending its application. Hence, relative studies will be continuously conducted. However, it should be noted that the most important method to remove the frost on outdoor coil surface is defrosting. During defrosting process, the energy that was used to heat indoor environment when normal heating was used to melt and evaporate the frost. Li [9] developed the dynamic model of defrosting of outdoor fin-tube heat exchanger based on measured surface temperature. Dong [10] experimentally measured the defrosting heat supplies and energy consumption during a reverse cycle defrosting operation. When the indoor fan was opened during defrosting, the heat supply from indoor air contributed to 71.8% of the total heat supplied, and 59.4% of the supplied energy was used for melting frost. Furthermore, the maximum defrosting efficiency could be up to 60.1%, which was obviously higher than the conventional defrosting with the indoor fan closed. Therefore, enough heat supplies could improve the defrosting efficiency effectively. For this purpose, Jiang [11–13] proposed a novel defrosting system for ASHP unit, which used phase change material to store energy and release it to heat refrigerant instead of indoor coil. The stored energy can come from discharged refrigerant of compressor, sub-cooling energy of refrigerant at the outlet of indoor coil, and even the waste heat of compressor. Fig. 2 shows the schematics of the defrosting system of ASHP unit using phase change energy storage. Using this method, the defrosting duration could be reduced distinctly, and the indoor environment could also improve effectively.

In addition, the components of the ASHP unit are also important for defrosting. At the end of the drain time, the method of the fan pre-start was effective in protecting the unit from being turned off owing to the discharge pressure protection [14]. Wang [15] added a refrigerant charge compensating into the ASHP unit instead of accumulator. When defrosting, it increased the refrigerant flow rate effectively, and thus the suction and discharge pressures and the power into the compressor were much larger, and leading to reduced defrosting duration.

The defrosting control method to make sure the initial and terminated points of defrosting is important for achieving defrosting when it is needed. Wang [16,17] investigated the characteristics of ASHP unit under two typical mal-defrost phenomena, and suggested using the photoelectric sensor to measure the thickness of frost and determined the initial point of defrosting. Jiang [18] proposed a novel defrosting control method based on the degree of refrigerant superheat at outlet of outdoor coil to make sure the initial point of defrosting.

2.2. Improving the performance in cold climate

Numerous researches on improving the performance of ASHP in cold climatic regions have been investigated in the last decade. According to the different ways of reducing the compression ratio, they can be classified as the following two systems.

2.2.1. Double stage coupled system

As early as in 2001, Ma [19] put forward double stage coupled system that consisted of an ASHP and a WSHP. As shown in Fig. 3, the ASHP supplied 10–20 °C water as the heat source of WSHP. The compression ratios and discharge temperatures of ASHP and WSHP were decreased due to the reducing of the temperature difference between evaporator and condenser. Wang [20,21] experimented and simulated the novel system. The experimental results showed that the system's COP increased by 20%, compared with that of ASHP. The simulation results found that the optimal temperature of middle water loop should be varied with operation conditions and the range was from 13 °C to 18 °C. In addition, the author's team analyzed and predicted the effect of applying the system in several Chinese northern cities. However, the initial cost and operation management would be major challenges in the process of popularization.

2.2.2. Two-stage/quasi-two-stage compression system

The major difference between two-stage compression system and quasi-two-stage compression system is the number of compressors. The former has one high-stage compressor and one low-stage compressor while the latter has only one compressor that can compress refrigeration twice in one shell. Ma [22] tested a quasi-two-stage heat pump system with internal heat exchanger. The experiment indicated that the COP increased by 14% while the discharge temperature decreased by 20 °C, compared with those of conventional system. In addition, they used flash tank instead of internal heat exchanger, as shown in Fig. 4(a and b). The results