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A Review of Defrosting Technologies for Air Source Heat Pumps

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Abstract

Air source heat pumps (ASHPs) are widely used in building energy efficiency due to their high performance and environmental benefits. However, in cold climates, frosting of ASHP evaporators during winter operation reduces heating efficiency, affects user comfort, and may even cause system shutdowns or permanent damage. Therefore, optimizing the defrosting cycle, implementing intelligent frost control, and accurately detecting frost thickness are key challenges in both research and practice. This paper reviews recent advancements in defrosting technologies for ASHPs, focusing on the limitations of existing methods and the development of emerging technologies. It also discusses intelligent control strategies, with an emphasis on intelligent frost detection and control systems. Finally, the paper outlines the future trends in ASHP defrosting technologies, aiming to provide a theoretical and technical foundation for their innovation and improvement.

Keywords

Air Source Heat Pump; Defrosting Technology; Intelligent Control; Frost Thickness.

1. Introduction

Air source heat pump (ASHP) technology, a prominent energy-efficient solution of the 21st century, has attracted significant global attention for its ability to recover low-grade heat and meet heating demands. Among various types of heat pumps, the ASHP is widely adopted due to its advantages, including convenient access to energy, stable performance, and ease of installation and use. ASHPs are commonly employed in residential air conditioning systems and heat pump water heaters.

Based on the reverse Carnot cycle, ASHPs extract low-temperature heat from ambient air and, through an efficient heat exchange process, convert it into high-temperature heat for space heating and hot water. This technology is characterized by high thermal efficiency and notable energy-saving and environmental benefits [1].

However, during winter operation, ASHPs are susceptible to frosting on the outdoor heat exchanger surfaces, especially in low-temperature environments. The accumulation of frost obstructs airflow, reduces heat transfer efficiency, and degrades the system's coefficient of performance (COP) and heating capacity [2,3]. To ensure efficient and stable operation of ASHPs in cold climates, it is essential to implement effective defrosting strategies. These strategies not only enhance system performance but also ensure long-term operational stability, thus supporting the broader application and adoption of ASHP technology.

2. Review of Domestic and International Research

The frosting problem of air source heat pumps (ASHPs) in low-temperature regions has been widely studied both domestically and internationally. The main defrosting methods include reverse cycle defrosting, heat medium bypass defrosting, heating defrosting, energy storage defrosting, external force defrosting, and active defrosting. These techniques aim to enhance ASHP performance and efficiency in cold climates.

2.1. Reverse cycle defrosting

Reverse cycle defrosting utilizes a four-way valve to switch the heat pump from heating to cooling mode [4]. In this process, the indoor and outdoor heat exchangers exchange roles, and the refrigerant releases heat to melt the frost on the outdoor exchanger. The defrosting cycle ends when the frost is cleared. This method requires only the activation of the four-way valve, without the need for additional devices or auxiliary heat sources.

Huang et al. [5] studied the impact of different throttling mechanisms on the defrosting time of reverse cycle defrosting, using a 22 mm diameter bypass copper pipe and a thermal expansion valve as throttling devices in a 55 kW air-source heat pump water heating system. Zhang Jun et al. [6] proposed a method for rapidly determining the optimal defrosting start point based on the maximum average heating capacity through a combination of theoretical analysis and experimental research. Qu et al. [7] noted that reverse cycle defrosting is widely used in air conditioning systems due to its ease of operation, absence of additional auxiliary equipment, and minimal drawbacks, such as indoor temperature fluctuations and power consumption. Hu et al. [8] introduced an improved reverse cycle defrosting method for air-source heat pumps, which reduced defrosting time by 3 minutes (38%) compared to the traditional method. Ding et al. [9] identified liquid storage in the suction line and the delayed response of the thermal expansion valve as key reasons for slow recovery to heating mode after defrosting, and proposed using a bypass solenoid valve to address this issue. Qu et al. [10] investigated the effect of electronic expansion valve (EEV) opening on defrosting performance, finding that the valve opening significantly impacts reverse cycle defrosting efficiency. Dong et al. [11] studied the heat supply and energy consumption during reverse cycle defrosting, determining the defrosting efficiency range for heat pump systems.

2.2. Refrigerant bypass defrosting

In the refrigerant bypass defrosting method, a bypass pipe is installed between the compressor outlet and the outdoor heat exchanger inlet. This system directs the high-temperature, high-pressure refrigerant gas discharged by the compressor into the outdoor heat exchanger, using its thermal energy to melt the frost. Since the four-way reversing valve does not need to change direction during this process, the system pressure remains stable, avoiding airflow noise and minimizing impact on the unit.

Moreover, the energy required for defrosting comes primarily from the heat accumulated by the compressor casing, with minimal reliance on indoor heat. This results in less indoor temperature fluctuation and better comfort. It is suitable for heat pump defrosting in small, medium, and large systems and is widely used due to its efficiency and low noise.

Studies by Huang et al. [12] indicate that while bypass defrosting takes longer than reverse cycle defrosting, it has little effect on indoor comfort. Liu Qingjiang et al. [13] found that the choice of electromagnetic valve significantly affects defrosting time and efficiency, with low-resistance valves reducing defrosting time and improving results. Zhan Wen et al. [14,15] discussed the principles and control logic of ammonia defrosting, highlighting the importance of selecting appropriate automatic defrosting valves, which play a crucial role in the design, operation, energy efficiency, safety, and management of ammonia refrigeration systems.

2.3. Heating defrosting

Heating defrosting mainly includes electric heating defrosting and solar-assisted defrosting [16]. Both methods utilize electrical or solar energy to heat the outdoor air entering the heat exchanger or the refrigerant working medium, thereby increasing the evaporating temperature and the compressor inlet refrigerant temperature, to achieve defrosting or delay frost formation.

Electric heating defrosting has advantages such as a simple system, thorough defrosting, and ease of control, making it suitable for small heat pump systems. Solar energy, being clean and renewable, helps reduce energy consumption, and is particularly beneficial in regions with abundant solar resources.

The electric heating element is typically installed before the heat exchanger, offering a simple structure and low design cost. Research shows that this method can maintain stable system operation for 200 minutes. At an outdoor temperature of 4°C, energy consumption is reduced by 32%, while heating capacity and COP increase by 9.1% and 71.1%, respectively [17,18]. Studies by K. Kwak et al. [19] show that at an outdoor temperature of 2°C, frost formation on the heat exchanger surface causes the evaporator temperature to drop rapidly to 12°C. At this point, the regular heat pump compressor stops, and a 2 kW indoor electric heater is used to stabilize the operation. A 1kW outdoor electric heater runs continuously, and the compressor operates throughout the defrosting period. Results indicate that, compared to traditional heat pumps, the electric heating method increases the heating capacity and COP by 38% and 57%, respectively.

Additionally, Yin et al. [20] investigated the application of an air bypass cycle combined with electric heating for defrosting in cold storage. The results show that compared to traditional electric heating, this method reduces the defrosting time by 62.1%, energy consumption by 61%, and temperature fluctuations by 70.1%, achieving a defrosting efficiency of 77.6%. Overall, stable heat supply (via heaters) ensures good system performance and maintains comfort in indoor environments.

However, electric heating defrosting consumes high-quality electricity, and some heat is lost to the surrounding cold environment, increasing energy consumption and reducing defrosting efficiency. Furthermore, the lifespan of electric heating elements or heat pipes is limited, and there are safety concerns. In refrigeration systems, electric heating defrosting has a significant impact on the temperature field of low-temperature cold storage, with only 15%-25% of the heat supplied being used for defrosting, while the rest is lost to the environment. To address this, Wang et al. [34] proposed an electric partition device to prevent heat from dissipating into the surrounding environment during defrosting. The results showed that, with the partition, temperature fluctuations within the cold air fan were reduced, temperature changes in the cold storage were minimized, energy consumption was significantly lower, and the defrosting time and energy efficiency were improved. This approach warrants further research for application in air-source heat pump defrosting systems.

2.4. Thermal energy storage defrosting

Building upon reverse cycle defrosting, thermal energy storage defrosting combines a thermal storage device with an air-source heat pump system [35]. During heating operation, a portion of the heat is stored in the thermal storage device and later released during the defrosting process. This method fundamentally addresses the energy shortage in traditional electric defrosting, improving the reliability and stability of air-source heat pump systems. It has become a widely studied defrosting approach.

2.5. External force defrosting

Defrosting can be enhanced by applying external forces, such as electric fields, magnetic fields, and ultrasound [36]. Electric and magnetic fields influence the growth of frost crystals by applying electrical or magnetic forces, stretching and fragmenting the crystals, which reduces adhesion to the heat exchanger surface and facilitates frost removal. Ultrasonic defrosting

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works by applying specific frequencies that resonate with the frost, disrupting its structure and aiding in its removal.

3. Emerging Defrosting Technologies for Air Source Heat Pumps

3.1. Thermodynamic defrosting

After frost accumulation, the frost layer is melted by increasing the evaporator surface temperature or the surrounding air temperature. Depending on the energy source, defrosting methods can be categorized into internal energy defrosting and external energy defrosting. Internal energy defrosting utilizes the compressor's heat, such as reverse cycle defrosting, hot gas bypass defrosting, and subcooling defrosting.

Reverse cycle defrosting is the most common method, but it presents several issues: (1) During reverse operation, the evaporator and condenser switch roles, which significantly differs from the normal operation, causing lower system efficiency; (2) The reduced refrigerant flow during reverse operation increases defrosting time; (3) After defrosting, the outdoor side may fail to complete condensation, risking compressor shutdown protection; (4) The reverse cycle decreases indoor thermal comfort during defrosting.

Hot gas bypass defrosting, introduced with advancements in control and manufacturing technologies, does not impact indoor thermal comfort and offers a more stable operation compared to reverse cycle defrosting. However, it requires longer defrosting time, and the suction superheat remains around 0°C during bypass operation, potentially lowering discharge temperature and risking compressor safety. From a design perspective, hot gas bypass defrosting requires larger units than reverse cycle systems, resulting in higher initial investment. Furthermore, its effectiveness is influenced by the control mechanism, electronic expansion valve opening, and bypass valve settings. Studies show that using well-matched electronic expansion valves and bypass valves can reduce defrosting time and energy consumption, while techniques like frost-point control further improve defrosting efficiency.

Subcooling defrosting stores some of the heat from the condensation process in a heat storage medium, which is released during defrosting. Similar to hot gas bypass defrosting, it has minimal impact on indoor comfort and can shorten defrosting time while reducing energy consumption. Additionally, fully condensing the refrigerant enhances heating efficiency. The defrosting performance depends on a well-designed control strategy. Heat storage defrosting can operate in parallel, series, or series-parallel configurations, with tests indicating that series operation is the most efficient. It has been found that the most challenging conditions for subcooling defrosting occur at -3°C. Compared to external heat source defrosting, subcooling defrosting has lower energy consumption and smaller equipment footprint. For example, in a system using a direct-condensing underfloor heating terminal and a water tank, subcooling defrosting significantly improves defrosting efficiency.

External energy defrosting utilizes heat generated outside the compressor. Methods include electric heating defrosting and solar-assisted defrosting systems. Electric heating defrosting directly or indirectly supplies the heat required for defrosting through external heating elements.

Compared to reverse cycle defrosting, electric heating provides ample defrosting energy, does not affect the refrigeration cycle, is cost-effective, and is easy to install. Its performance depends on the heating element's material, installation position, and arrangement. Although electric heaters directly heat the frost layer and surrounding environment, resulting in additional energy consumption, they are effective in regions with high frost accumulation, such as the Yangtze River basin, where the air source heat pump often experiences significant frosting. To improve energy utilization, circulating heated water may be used to enhance frost removal efficiency.

Solar-assisted defrosting systems have higher energy savings but require additional solar collectors and thermal storage devices, leading to larger system size and higher initial costs. Current research on improving the defrosting performance of such systems focuses on heat exchanger designs, such as multi-tube heat exchangers with multiple heat transfer processes, solar-assisted heat pump systems, and cylindrical shell-and-tube phase-change thermal storage systems.

3.2. Non-thermal defrosting

Non-thermal defrosting methods intervene directly in the formation and growth of frost layers, making them easier to remove. Current research includes techniques such as ultrasonic, electric, magnetic fields, and hydrophobic coatings. These methods do not affect indoor thermal comfort during defrosting. Ultrasonic defrosting primarily alters the shape and size of water droplets and frost crystals. Specific ultrasonic frequencies can reduce droplet and crystal volume, increasing droplet removal efficiency by up to 70%, and intermittent use can lower energy consumption during defrosting [21][22][23]. Electric field defrosting utilizes the influence of the electric field on water molecule diffusion, causing them to arrange in a more orderly manner. Continuous or intermittent electric fields can lead to the formation of needle-like frost crystals on cold surfaces, which then fall off naturally [24][25]. Various types of electric fields, such as high-voltage electrostatic fields and swept-frequency high-voltage fields, have been shown to be effective [26][27]. Magnetic field defrosting affects the formation, generation process, and morphology of frost, making the droplets more uniform and the structure looser, facilitating removal [28]. Hydrophobic coatings, with high contact angles on their surfaces, delay the nucleation of frost compared to flat surfaces, making frost removal easier. Advanced hydrophobic coatings, inspired by biomimicry, have increased the contact angle from 90° to 162° [29-33]. While non-thermal defrosting methods show promise, they are still less mature for large-scale applications and come with higher costs compared to thermal methods.

4. Methods for Defrosting Control of Air Source Heat Pump

In the actual defrosting of air source heat pump, the "false defrosting" failure caused by the improper selection of defrosting start and end point often occurs, and premature defrosting will lead to frequent defrosting operation and increase power consumption. After defrosting, the heat produced by the unit decreases and the indoor thermal comfort becomes worse.

4.1. Defrost control method for direct measurement of frost thickness

Frost layer thickness is the most important and direct factor affecting the frosting performance of air source heat pump. If it can be accurately measured, it can provide a reliable basis for the selection of defrosting control points.

(1) Laser thickness measurement: Laser thickness measurement technology is to use two laser displacement sensors to shoot up and down, respectively, to measure the position of the upper and lower surface of the frost layer, and to calculate the thickness of the frost layer. The advantage of laser thickness measurement is that it uses a non-contact measurement, which is more accurate than a contact thickness gauge, and does not lose accuracy due to wear.

(2) Microscopic imaging: microscopic imaging technology is a method to obtain high-definition two-dimensional images of frost formation by microcamera, and then process the frost formation images by image processing technology to output the thickness of the frost layer.

(3) Probe micrometer: The probe micrometer technology for measuring the thickness of the frost layer is a method to obtain three-dimensional images of the frost layer by scanning the atoms between the probe and the surface of the frost layer

(4) Photoelectrical conversion: induction of light intensity changes through the output voltage, when the beam is not blocked by the frost layer (no frost) output low voltage; If the beam is

blocked by the frost layer (when there is frost), the output of high voltage, the whole process uses light as the medium to achieve electric-opto-electrical conversion and transmission.

(5) Image processing: The process of defrosting control using image processing technology includes frost image acquisition, target region setting, gray level analysis, edge determination and frost layer thickness output.

4.2. Defrosting control methods based on intelligent algorithms

With advancements in technology, defrosting control methods have become increasingly intelligent. Intelligent algorithms use input variables such as outdoor air temperature, humidity, and compressor runtime, along with defrost control rules, to determine the appropriate defrosting conditions and control the start and stop of defrosting actions.

(1) Fuzzy logic control: This method processes input variables, such as outdoor temperature, humidity, and compressor runtime, through fuzzification and fuzzy inference. Based on the defrosting performance, the fuzzy control rules are evaluated and adjusted if necessary. This cyclical process ensures that defrosting is performed appropriately according to the system's operating conditions.

(2) Artificial neural networks: In this approach, an artificial neural network is used for defrosting control by establishing prediction models for frosting amount, defrosting duration, and intervals. These models are based on specific algorithms, which predict the optimal defrost start and stop points, thus enabling automated and efficient defrosting control.

5. Conclusion

Frost formation remains a significant barrier to the widespread adoption of air-source heat pumps, particularly in low-temperature regions. Extensive research has been conducted on defrosting techniques to enhance their performance under such conditions. Different defrosting methods have distinct advantages, with frost formation closely linked to outdoor temperature and humidity. The variability in temperature and humidity across regions, locations, and time periods directly affects the defrosting efficiency of the units. Based on a review of the current state of research, this paper analyzes the existing challenges in defrosting technologies and provides an outlook on future advancements.

At present, defrosting technologies for air-source heat pumps still face limitations, particularly in improving the efficiency and reliability of traditional defrosting methods. Although thermal energy storage-based defrosting has shown promising results, its practical application remains limited. Further research is needed to develop compact, cost-effective thermal storage systems with larger storage capacities. New defrosting methods utilizing external electric fields, magnetic fields, or ultrasound also show significant potential, though further investigation into the defrosting mechanisms and application of external forces on outdoor heat exchangers is required.

Direct measurement of frost thickness offers high precision for monitoring frost accumulation but is constrained by factors such as space and cost, making it difficult to implement in real-world air-source heat pump systems. Indirect monitoring methods, such as the temperature-time method, are widely used due to their simplicity and lack of additional equipment. Future research should focus on determining optimal parameter ranges for defrost initiation and termination, particularly regarding evaporator fin temperatures, and how these parameters vary with different air-source heat pump models. This will enhance the adaptability of defrosting control methods across various regions and brands.

Additionally, defrosting control methods based on intelligent algorithms require sufficient and accurate training data to establish effective control strategies. Given the rapid development of big data and artificial intelligence, further research into the application of AI for defrosting control is essential. An appropriate evaluation system could improve the performance of different defrosting control methods in various regions and equipment. It is recommended that future evaluation frameworks incorporate metrics such as energy consumption during a defrost cycle, unit stability, and indoor thermal comfort, aiming to maximize the defrosting control effectiveness and economic efficiency.

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