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Characteristics of an air source heat pump with novel photoelectric sensors during periodic frost–defrost cycles

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HIGHLIGHTS

► Characteristics of the ASHP under periodic frost–defrost cycles are tested.
► Great deficiency is found for the characteristics of ASHP during the test.
► A novel type of photoelectric sensor TEPS is proposed and also tested in this paper.
► Test results confirm the expected potential for TEPS to control defrosting process.
► The agreeable structure configuration for the proposed TEPS is achieved.

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ABSTRACT

To avoid mal-defrost phenomenon, an innovative photoelectric sensor is developed and presented in this paper. It is referred to as "Tube Encircled Photoelectric Sensor" (TEPS). Experiments are carried out in a controlled environmental chamber under standard frosting conditions. Ten TEPSs in 4 different models are tested on a commercial size air source heat pump with the nominal heating capacity of 60 kW. The characteristics of the air source heat pump, together with the performance of the TEPSs are investigated during 9 periodic frost–defrost cycles. Compared with the original defrosting control strategy equipped by the manufacturer, the proposed TEPS sensor reveals its potential ability to accurately control the defrosting process. Experimental results demonstrate that TEPSs can substantially prolong defrost intervals from 28.8 min to 52 min under the experimental conditions, and the number of defrost cycles can be reduced from 9 to 5. The performance improvement is found to be 6% to the heating efficiency, and 5% to the COP.

1. Introduction

The frost is initiated when the heat exchanger surface temperature is below both the environmental dew point and freezing temperature. The frosting often exerts negative effects to the performance of the air source heat pump or other refrigeration units. According to the study of Lenic [1], the overall heat transfer coefficient decreases 17% when the average frost layer thickness reached 1.0 mm. From the test results of Silva et al. [2], the cooling capacity drops by 40% after 30 min of frosting process for a 4.7 FPC (Fins per Centimeter) evaporator, at a supercooling value of 14.5 °C. In the previous study of Wang [3], the heating capacity of the ASHP decreased 29% when the outdoor heat exchanger was frosted for over 60 min. Therefore, defrosting cycles must be implemented to restore the original capacity of the evaporator and improve the energy efficiency of a refrigeration system or ASHP unit.

To improve the energy efficiency of the ASHP, concrete works have been conducted to advance the defrosting methods and control strategies. As the frost thickness is not easily measured, the defrosting control strategies are normally set up in the following ways. One is monitoring the formation conditions of ice crystal. The frost formation and growth is a quite transient process with dynamic heat and mass transfer. This process is impacted by six primary parameters, air temperature, air relative humidity, air velocity, air cleanliness, and the temperature and wettability of the heat exchanger surface. It is a fairly hard work to monitor all these parameters simultaneously in practical applications. Therefore, defrosting control strategies [4–6] belonging to this type will certainly lead to mal-defrost. The other strategy is monitoring the by-products of the frosting. Once the frost built up on the heat

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Nomenclature

c_p	specific heat at constant pressure, J kg^{-1} K^{-1}
$\dot{m}_w$	water mass flow rate, kg s^{-1}
$\dot{Q}_{DF}$	efficient heating energy with several defrosting cycles, J
$\dot{Q}_{NF}$	efficient heating energy without defrosting cycles, J
$\dot{q}_{dc}$	heating capacity during the defrosting cycle, W
$\dot{q}_{hc}$	heating capacity during the heating cycle, W
t_{dc}	time for defrosting cycle, s
t_{df}	time for defrosting section, s
t_{hc}	time for the heating cycle, s
t_{rc}	time for the heating capacity recovery, s
W	electrical energy consumption of the units, J
$\Delta\dot{Q}_L$	the loss of the efficient heating energy, J
ΔT	temperature difference between supply and return water, °C

Greek symbols

η	heating efficiency

exchanger surface, the pressure drop varies, which leads to a variation of the operation point for the fan, and the throttle valve acts to reduce the refrigerant flow rate, which leads to the decrease of the evaporating temperature and the heating capacity, as demonstrated in literature [7–9]. It should be noted that the above results can also be originated by some other operations, like upload or offload. So, mal-defrost may still happen. The experimental results of Liang [10] and Datta [11,12] indicate that some defrosting control strategies are set up based on the method of artificial intelligence. They are usually not reliable due to a lack of adequate learning samples. Some defrosting strategies [13–15] monitor variations in the heat transfer process. They are also not applicable due to difficulties in implementation techniques. Therefore, the mal-defrost will certainly happen if the defrosting strategy is not based on the direct information, especially frost thickness.

Some methods have been applied in the laboratory to measure the frost thickness directly, like infrared camera [16], low energy laser beam [17], microscope [18–20], micrometer [21,22]. Due to the rigid requirement of operating conditions and unsuitable sizes, those methods are just appropriate for laboratory experiments and not suitable for the practical machines.

The feasibility of the photoelectric technology in the laboratory testing has been reported by Lee [23]. In the previous study of Wang [24], two agreeable properties of the photoelectric technology, "On-off" and "Linear", have been demonstrated by experiments. The characteristics (electric current, environment temperature, metal surface temperature, light intensity and sensor location) affecting the "On-off" property were investigated. According to the property of "linear", a generalized correlation between the output signal of the photoelectric sensor and the frost height was proposed with total 600 experimental data [25].

The purpose of this study is to further prove the feasibility of using the photoelectric sensors in practical applications. An innovative type of photoelectric sensor, namely Tube Encircled Photoelectric Sensor (TEPS) is proposed in this paper. Experiments are carried out in a controlled environmental chamber under standard frosting conditions. The characteristics of an ASHP unit with the nominal heating capacity of 60 kW are tested during periodic frost–defrost cycles. The performances of the TEPS are also investigated. Compared with the original defrost control strategy used by the manufacturer, TEPSs present convincing potential to accurately control the defrosting operation for ASHP units.

2. TEPS

According to the research of Wang [25], a common photoelectric sensor is composed of an emitter and a receiver. Once driven with current via an electrical source, the emitter emits constant infrared rays to the receiver through a passage. Then the infrared energy can be absorbed and transformed into current by the receiver. Under the condition that no frost exists in the passage, most of the infrared energy can be absorbed by the receiver and the output voltage remains at its minimum value. With the accumulation of frost, the infrared energy arriving at the receiver is weakened or interrupted and the output voltage increases correspondingly. Finally, when the passage is fully filled with frost, little infrared energy reaches the receiver and the output voltage reaches its maximum value. Based on this mechanism, in this paper the photoelectric sensor is introduced for frost detection within the ASHP unit.

As the typical fin space is 4–10 FPC, it is not practical to locate a photoelectric sensor between fins. Also, it is not easy to set the emitter and receiver on a line of sight over a long distance because a small deviation will lead to a large discrepancy in the results. So, this study locates the sensors on the refrigerant distribution pipes. The original configuration of the photoelectric sensor is modified. The developed sensor is referred as Tube Encircled Photoelectric Sensor (TEPS).

Fig. 1 presents the configuration of the proposed TEPS. It consists of a photoelectric sensor, circuit board, connection frame and test section. The circuit board serves as the medium between the TEPS and driver card. It provides current to the emitter and transfers output voltage to the driver card. The connection frame is the main structure for TEPSs, which ensures each two sensors coupled together with the tube. The test section is made of heat transfer material, like aluminum or copper. To make it firmly contact with the tube, it is embedded in the connection frame, and the bond between the test section and tube is filled with thermal conductive silicone. Thus, frost accumulating on the test surface can be easily monitored.

It needs to be highlighted that frost growth on the test surface is only similar, but not identical to that on the heat exchanger surface. To overcome this problem, a structural parameter called initial position, the spacing from test surface to the photoelectric sensor, is applied to weaken the discrepancy. The initial spacing is marked in Fig. 1a. The original configuration of photoelectric sensor and developed TEPS are presented in Fig. 1b.

3. Experimental system

3.1. Experimental apparatus

Experiments are conducted in a controlled environmental chamber, with dimensions 8.2 m × 7.0 m × 6.0 m (length × width × height). It is built for the purpose evaluating the performance of commercial size ASHP units with a heating capacity range of 55 kW–350 kW, cooling capacity 50 kW–300 kW, power consumption 20 kW–120 kW and air flow rate 8.6 m^3 h^{-1} to 52 m^3 h^{-1}. The test conditions can be controlled within the ranges of ±0.5 °C for water temperature, ±1.0 °C for dry-bulb temperature, and ±0.5 °C for wet-bulb temperature.

An ASHP unit with nominal heating capacity of 60 kW is utilized for the test. The schematic of the experimental cycles are shown in Fig. 2a. It consists of two separate units: unit I and unit II. The refrigerant cycles of the two units are totally independent. However, the condenser coils of each unit couple together and exchange thermal energy with the water loop simultaneously. Two V-type fin-tube heat exchangers are arranged. Each heat exchanger