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

Wei Wang*, Jing Xiao, Yingchao Feng, Qingci Guo, Lincheng Wang

The Department of Building Environment and Facility Engineering, The College of Architecture and Civil Engineering, Beijing University of Technology, No. 100 Pingleyuan Road, Chaoyang District, Beijing 100124, China

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
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 position) 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 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).

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 m³ h⁻¹ to 52 m³ 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

<table>
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<th>Nomenclature</th>
<th>Description</th>
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<tr>
<td>(c_p)</td>
<td>specific heat at constant pressure, J kg⁻¹ K⁻¹</td>
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<tr>
<td>(m_w)</td>
<td>water mass flow rate, kg s⁻¹</td>
</tr>
<tr>
<td>(Q_{DF})</td>
<td>efficient heating energy with several defrosting cycles, J</td>
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<tr>
<td>(Q_{NDEF})</td>
<td>efficient heating energy without defrosting cycles, J</td>
</tr>
<tr>
<td>(\dot{q}_{he})</td>
<td>heating capacity during the defrosting cycle, W</td>
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<tr>
<td>(\tau_{df})</td>
<td>time for defrosting section, s</td>
</tr>
<tr>
<td>(\tau_{he})</td>
<td>time for the heating cycle, s</td>
</tr>
<tr>
<td>(\tau_{ref})</td>
<td>time for the heating capacity recovery, s</td>
</tr>
<tr>
<td>(W)</td>
<td>electrical energy consumption of the units, J</td>
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<tr>
<td>(\Delta Q_{L})</td>
<td>the loss of the efficient heating energy, J</td>
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<td>(\Delta T)</td>
<td>temperature difference between supply and return water, °C</td>
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<td>(\eta)</td>
<td>heating efficiency</td>
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Fig. 1. Schematic and image of TEPS.

Fig. 2. Tested ASHP and TEPS.
is equipped with a 3-row, 4-circuit coil with 15 distribution lines. The outer diameters of the copper tubes are 10 mm for the heat exchanger and 6 mm for the distribution lines. Each unit is equipped with a reciprocating compressor, and a four-way reversing valve, which enables the units to defrost separately in reverse cycle. The image of the tested ASHP is shown in Fig. 2b.

As shown in Fig. 2c, the TEPSs are located on the refrigerant distribution lines. The TEPS units are coupled in pairs. In total ten TEPSs are tested in this study. They are chosen from 4 groups with different models. The setup information for the tested TEPSs is listed in Table 1. Under the same operating conditions, all the TEPSs are attached to the unit I in this study.

The refrigerant circuit and hot water supply system are instrumented with PT100 thermocouples to monitor the variation of temperature. The humidity of the environment is measured by a humidity sensor VAIASA HMT100 with an accuracy of ±1.7% RH. Pressure transducers JYB-KO-PAG are placed in the refrigerant lines near the thermocouples to monitor the variation of pressures. A power sensor YOKOGAWA WT-230 with the range of 15 V, 0.5 A is used to monitor the ASHP power input. A water flow-meter AE204MG is used to collect the flow rate variation of the hot water supply with an accuracy of ±0.1% in the range of 0 m s⁻¹ to 10 m s⁻¹. A driver card is developed to drive the TEPSs with current and then to collect the output voltage from them. A digital camera (Canon A1100, 12 megapixels) is used to capture the images of the heat exchanger under frosting condition. The detail information about the instruments is presented in Table 2.

3.2. Test procedure

The experiments are conducted under the standard frost and defrost test conditions of dry bulb and wet bulb temperature at 2 °C and 1 °C respectively, and hot water inlet temperature is controlled at 40 °C with a constant flow rate of 10 m³ h⁻¹. These conditions are stipulated by Chinese standard GB/T 18430-2007. The two ASHP units defrost alternately. When one unit runs in the defrosting cycle, the other one stops. The test data collected from each sensor can be automatically sent to a computer via a data acquisition switch unit. The output voltages of 10 TEPS sensors are monitored every 5 s.

3.3. Defrosting control strategy

The defrosting control strategy of the tested ASHP is a self-adaptive control strategy based on 5 parameters.

1) Fin temperature,
2) Variation rate of fin temperature,
3) Environmental temperature,
4) Difference between the fin and environmental temperature,
5) Time for heating cycle.

This defrosting strategy was developed by the manufacturers with the original aim to defrost on demand. It is expected to be adaptive to variations in the environmental conditions. The initiation of a defrost cycle is determined based on the above five parameters following a complex control logic. The termination of the defrosting cycle is decided when the fin temperature reaches 15 °C. As the defrosting control logic contains 4 pages of document, it can not be fully listed in this paper, however the variation rate of the fin temperature is described as the most important parameter in this strategy. By theoretical analysis, it is found that the fin temperature will drop suddenly once the frost forms.

Although this defrosting strategy is carefully designed, it is actually a modified temperature-time method, and is still based on the indirect information. According to the study of Baxter [26], there is approximately 27% of the defrosting is carried out in the conditions of no frost accumulation, due to the time—temperature defrost controller. Thus, in the practical applications, mal-defrost phenomena will still happen for the tested ASHP units.

3.4. Data reduction method

To obtain the overall characteristics of the ASHP units during the periodical frost—defrost cycles, several parameters are defined. Fig. 3 is used to illustrate the method of analyzing these parameters. The figure is drawn by the instant heating capacity q VS the time t. Two defrosting cycles are involved in the figure. The time for each defrosting cycle t₉ₕ consists of two sections. The first is the defrosting section t₉ₕ, during which the refrigerant is in the reverse cycle, and the heating capacity q₉ₕ drops quickly. The other is the section for the heating capacity recovery t₉ₑ, during which q₉ₑ returns to the nominal value. The period for the heating cycle is defined as the t₉ₑ. The heating capacity q₉ₑ in this time remains relatively stable. Though the time t₉ₑ belongs to the heating cycle, the heating capacity is found to below the normal value during this time interval. So, it is brought into the group of defrosting cycle.

A useful parameter, heating efficiency n is put forward to evaluate the efficient heating energy gained by the users in the period

![Fig. 3. Analysis of the parameters for frost—defrost cycles.](image-url)
with several defrosting cycles. It also represents the level of heating energy loss due to the occurrence of the defrosting cycles. It is defined as,

\[ \eta = \frac{Q_{\text{DF}}}{Q_{\text{NF}}} \leq 1 \]  

(1)

where \( Q_{\text{DF}} \) is the efficient heating energy gained by the users in the heating period with several defrosting cycles, \( Q_{\text{NF}} \) is the heating energy in the same heating period with no defrosting cycles. It can be calculated by supposing that defrosting cycles are totally replaced by the heating cycles. The dashed lines in Fig. 3 are used to accomplish this assumption. The area below the dashed lines is the loss of the efficient heating energies \( \Delta Q_L \) due to the defrosting cycles.

The above parameters can be determined as follows,

\[ Q_{\text{NF}} = q_{\text{hc}} \times t \]  

(2)

\[ Q_{\text{DF}} = Q_{\text{NF}} - \sum \Delta Q_L \]  

(3)

where \( \Delta Q_L \) is the loss of the efficient heating energies in the defrosting cycles. It can be calculated from the test data as follows.

\[ \Delta Q_L = \sum_{i=1}^{n} (q_{\text{hc}} - \hat{q}_{\text{dc}}) \times (t_i - t_{i-1}) \]  

(4)

The number \( n \) is decided by the length of a defrosting cycle \( t_{\text{dc}} \) and the data acquisition interval, which is 6 s in this study.

The integrated cyclic COP is defined as the ratio of the heating energy \( Q_{\text{DF}} \) over the integrated energy consumption.

\[ \text{COP} = \frac{Q_{\text{DF}}}{W} \]  

(5)

The \( Q_{\text{DF}} \) can also be calculated by the measurable quantities, like the water flow rate \( m_w \) and temperature difference \( \Delta T \) between water inlet and outlet in the space heating system.

\[ Q_{\text{DF}} = m_w \times C_p \times \Delta T \]  

(6)

The integrated energy consumption includes the compressors and fans.

4. Result and discussion

4.1. Operating characteristics of ASHP

The operating characteristics of the tested units are presented in Fig. 4 ~10. As shown in Fig. 4, experiments are carried out over more than 4 h. In the first hour, the dry bulb temperature drops from 25.7 °C to 2 °C, and wet bulb temperature from 20.6 °C to 1 °C, respectively. Then, the desirable test conditions are set up. In the subsequent 3 h, the test conditions are maintained in a stable state. The only instability detected is from small fluctuations during defrosting cycles.

The suction and discharge temperatures of the compressors for unit I and unit II are presented in Fig. 5. During defrosting cycles, compressor discharge temperature drops quickly from 80 °C to 40 °C while the suction temperature increases from −2 °C to 30 °C. These data help to identify the defrosting cycles. According to Table 3, there are nine frost—defrost cycles during the test period. For unit I, five defrosting cycles are initiated with the intervals of 30 min, 63 min, 34 min, 56 min and 49 min. For unit II, 4 defrosting cycles are initiated with the intervals of 35 min, 83 min, 58 min, and 70 min.

Fig. 6 presents the time distributions for each defrosting cycle. The overall time for defrosting cycle \( t_{\text{dc}} \) varies from 222 s to 360 s with an average value of 296 s. This indicates the typical length of \( t_{\text{dc}} \) is around 5 min. This value is decided by the lengths of \( t_{\text{df}} \) (with average weight of 45%) and \( t_{\text{rc}} \) (with average weight of 55%). In this study, the \( t_{\text{df}} \) fluctuates from 90 s to 179 s with an average value of 136 s. According to Fig. 6, the \( t_{\text{df}} \) and \( t_{\text{rc}} \) reveal similar patterns. It indicates that the \( t_{\text{df}} \) is influenced by the \( t_{\text{rc}} \), which is actually related to the frosting level on the heat exchanger. In addition, the defrosting interval between unit I and unit II is also an important factor influencing the \( t_{\text{df}} \). As stated above, when one unit is in the defrosting cycle, the other stops running. The frost will melt naturally for the stopped unit. So, the \( t_{\text{df}} \) is usually much shorter for the unit with later defrosting sequence. For instance, the defrosting interval between No. 6 and No. 7 is only 6 min. The \( t_{\text{df}} \) is only 120 s for the No. 7 defrosting cycle despite the previous \( t_{\text{rc}} \) reaching 56 min. The other section, \( t_{\text{rc}} \) remains relatively stable around 160 s. This indicates that the time for the heating capacity recovery \( t_{\text{rc}} \) is not a variable under certain test conditions. It is independent of \( t_{\text{df}} \). By summing the length for each defrosting cycle, the total defrosting cycle time is 44.4 min, which occupies 18% of the whole test period. It should be highlighted that this period is the time for the ASHP units operating far below the average heating capacity in the heating cycle. The results reflect the main defects for the refrigerant reversed-cycle defrosting method.

The patterns of outlet and inlet water temperature are shown in Fig. 7. In the heating cycles, they can remain relatively stable at 45 °C and 40 °C, respectively. However, in the defrosting cycles, the outlet temperature drops quickly from 45 °C to 38 °C. At each defrosting cycle, the outlet water temperature can drop even lower than the inlet water temperature. The maximum temperature difference for inlet and outlet water temperature may reach 3.5 °C. In total, there are 17.5 min for the units to run under this condition,
which is the most unexpected occurrence, as the units are taking heat from the water loop instead of supplying heat to it.

Fig. 8 confirms the above results. From the patterns, the heating capacity and the input power keeps stable at 49.8 kW, and 16.8 kW during the heating cycle. However, great loss of ΔQ_L is found in the frequent defrosting cycles. The total heating loss during the defrosting cycles is 97.2 MJ, which is 13.4% of the total heating capacity. This means the heating efficiency η is 86.6% in this test.

The total integrated energy consumption is 31.2 MJ for the defrosting cycles. And the average loss of the heating quantity and the energy consumption for each defrosting cycle are 10.8 MJ and 3.5 MJ, respectively.

As shown in Figs. 7 and 8, the defrosting cycles can not be completely repeated even in same operating conditions. This is caused by the defrost sequence of the two units. When a unit runs in the defrosting cycle, the other one stops. The frost on the stopped unit will melt during this period. This process impacts the frosting and defrosting cycles. So, no repeated results are found.

In addition, it should be noted that no large decreases for the heating capacity are found while the defrosting cycles are in progress. This means that the frost accumulating on the heat exchanger is not strong enough to influence the performance of the ASHP units. The frosting images shown in Fig. 9 validate this conclusion. The images at the 30th min and 35th min reveal that there is only a small amount of frost accumulating on the heat exchanger. The defrosting cycles are definitely unnecessary at those points. Though heavier frost is found at the 118th min, 127th min, 183th min and 234th min, the typical frost thicknesses at those moments are no more than 0.5 mm. Frost exerts little effect on the performance of the ASHP; thus it is inappropriate to begin defrosting cycles at those points. The above results confirm that mal-defrost appears in this study.
The variation of COP is shown in Fig. 10. As the negative values for COP have little practical meaning, the patterns only reveal its positive parts. The figure reveals that COP remains stable at 3.0 all along the heating cycle even at the beginning of each defrosting cycle. No apparent deficiency is found for the COP except during the periods of defrosting cycles. The integrated cyclic COP for the test period is 2.76. This discrepancy is also caused by the defrosting cycles.

In conclusion, the frequent and unnecessary defrosting cycles often lead to undesirable performance for the ASHP, including great loss of heating capacity, frequent drop for the heating efficiency, large decrease for the COP and additional strong influences on the users’ heating effect. To resolve the above issues, the technology of defrosting control needs to be advanced.

### 4.2. Output voltage of TEPS

Fig. 11 reveals the output voltages of TEPSs during the above frost-defrost cycles. As all TEPSs are installed on the unit I, the output voltages mainly reflect the frosting levels. However, as the two units operate under similar conditions, the output voltages can also serve as the references for the unit II. In Fig. 11a–c, the output voltages increase with the frosting process and decrease with the defrosting cycles. This demonstrates that the TEPSs from the Model I to III are sensitive to the variation of the frost growth. According to the previous study of Wang [17], the response value of the output voltage for starting up a defrosting control is 9.0 V. From the test results of Model I to III, the output voltages at the 30th min (No.1) are just around 4.0 V, 6.0 V and 7.0 V respectively, which are far below the nominal response value of 9.0 V. Similar situations are found at the 127th min (No.5). These data indicate that unit I will not defrost at the above points if controlled by the TEPSs. Since the two units operate under similar conditions, it is reasonable to conclude that the defrost controls for unit II at the 35th min (No.2), 118th min (No.4) will also not be started by the TEPSs. These results coincide with the frosting images in Fig. 9. In this way, the total number of defrosting cycles can be reduced from 9 to 5 by using the TEPSs for defrost-cycle control. In addition, the output voltages of TEPSs at the 93th min, 183th min and 234th min are just 8.7 V, 8.8 V and 8.9 V. None of them reach the response value of 9.0 V. These data indicate that the above points are not appropriate for initiating a defrosting cycle. This conclusion also coincides with the images of the frosting level shown in Fig. 9. By extending the data along with their trend curves, the initiation points for defrosting cycles of the Model I, II and III can be expected to be prolonged to points A, B and C.
Fig. 11. Output voltages of photoelectric sensors.
The initial output voltages of Model IV start at 7.0 V instead of 0 V. In contrast, the output voltages of Model IV reveal a vague pattern. It can be concluded that the initial position of 1.0 mm is an agreeable structure value for the TEPSs. In contrast, the output voltages of Model IV reveal a vague pattern. The initial output voltages of Model IV start at 7.0 V instead of 0 V. The “on-off” characteristic is difficult to determine. The reason for this is that the initial position of this group is only 0.4 mm, which leads to the blockage of the optical passage by the test section. So, the configuration of TEPSs in Model IV is not suitable for practical applications. To get desirable characteristics for monitoring the frost, the initial position of TEPS needs to be higher than 0.4 mm.

It should be noted that different behavior can be found for sensors in the same model. Take Fig. 11a as an example, though four sensors belong to the same model, some slight differences can still be observed. The different behavior is mainly caused by the location of the sensor. Mal-distribution of refrigerant is a common problem for the heat exchangers. To eliminate this impact, several sensors need to be loaded on the heat exchanger, and the defrost demand is decided through analyzing output signals of these sensors. As the sensor is fairly cheap, it will not add too much initial cost for the ASHP unit.

4.3. Discussion

4.3.1. Improvement of heating efficiency

In this study, the TEPSs are used to monitor the frosting levels on the test units other than control the frost—defrost process. However, based on the test data, the improvement of the heating efficiency by using the TEPSs can still be expected. As stated in section 4.2, the total number of defrosting cycles can be reduced from 9 to 5, and the heating cycles can be further prolonged by the application of TEPSs. This means that the number of defrosting cycles will be less than 5. As calculated in section 4.1, the average heating capacity and input power during the heating cycle is 49.8 kW and 16.8 kW respectively. For each defrosting cycle, the average loss of the efficient heating energy is 10.8 MJ, and the energy consumption is 3.5 MJ. By submitting those data to Eqs. (1)–(3) and (5), the patterns of heating efficiency and the COP under different number of defrosting cycles can be obtained, as presented in Fig. 12. Referring to the figure, the heating efficiency will be improved from 86.6% to 92.6% with the defrosting numbers cutting from 9 to 5. The COP will also increase from 2.74 to 2.85, a 5% improvement. Based on the above analysis, an improvement of the heating efficiency and the COP can be expected with the control of TEPSs.

Predictions stated above are concluded based on the simplification that the COP is not varied with the accumulation of frost. According to the author’s previous study, the COP will decrease around 30% when the heat exchanger is fully covered by frost. So, reducing the defrosting frequency, the COP will decrease gradually. The optimum defrosting frequency should be discussed between the COP decrease with the frosting and the loss during the defrosting mode. In the ongoing work, the optimal defrosting strategy will be determined with the objective to achieve the maximum value of COP.

4.3.2. How to use the sensor in defrosting control

As demonstrated above, output signals of TEPS are varied with the frosting and defrosting process. During these processes, the output voltage switches from 0.2 V to 9 V. These two values exhibit the “on–off” control property. The minimal value 0.2 V can be applied to judge whether the frost began to form or whether the defrosting is completed. The max value of 9 V can be applied to judge whether the refrigerator needs defrosting. This property can be applied as the judgment of the defrost-control strategy. The different behavior of the sensor can be eliminated by putting a few sensors on the heat exchanger. In addition, the optimal distributions of the sensor and the optimal location for the sensor are also ongoing research topics.

5. Conclusion

Characteristics of an air source heat pump during periodical frost—defrost cycles, together with the performance of the proposed "Tube Encircled Photoelectric Sensor" (TEPS) are presented in this paper. A commercial size ASHP with ten TEPSs in different structural configurations is tested under standard frosting conditions in a controlled environmental chamber. The conclusions are as follows:

1) Under the test conditions, the typical length for each defrosting cycle $t_{df}$ is found to be 5 min, which consists of the defrosting section $t_{df}$ (with average weight of 45%) and the heating capacity recovery section $t_{rc}$ (with average weight of 55%). The $t_{df}$ fluctuates from 90 s to 179 s with an average value 136 s. It is influenced by the frosting level on the heat exchanger or the length of heating cycle, and the defrosting interval between unit I and unit II. The $t_{rc}$ remains relatively stable around 160 s.
2) The total time for defrosting cycle is 44.4 min, which occupies 18% of the whole test period. The occurrences of those defrosting cycles lead to 97.2 MJ of the heating energy loss with an undesirable heating efficiency $\eta$ of 86.6%. The integrated cyclic COP also drops from 3.0 to 2.76 due to the defrosting cycles.
3) Referring to the test data of TEPSs, if controlled by the TEPSs, the improvements for the heating efficiency and COP can be expected by cutting down the unnecessary defrosting cycles, and prolonging the heating cycles. In this study, the number of defrosting cycles can be reduced from 9 to 5, and the heating
cycles will certainly be extended. The heating efficiency can be improved to 92.6%, and COP can be improved to 2.85.

5) TEPSs with an initial spacing of 1.0 mm present an agreeable ability to monitor the frosting levels. It is suitable to act as the sensor in the practical defrosting control. However, the initial spacing lower than 0.4 mm is undesirable to the practical application.

Though TEPS exhibits excellent characteristics in monitoring the frosting levels, ongoing work will focus on developing optimal structure parameters of TEPS, advancing the defrosting control strategy. The characteristics of the ASHP controlled by the TEPSs under standard frosting conditions, the optimal distributions of the sensor and the optimal location for the sensor will be investigated in the ongoing studies.

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References