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An experimental study on the negative effects of downwards flow of the melted frost over a multi-circuit outdoor coil in an air source heat pump during reverse cycle defrosting

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HIGHLIGHTS

- A special experimental rig was built and its details are reported.
- The negative effects of downwards flowing of the melted frost were shown.
- Defrosting duration was shortened after installing water collecting trays.
- Temperature of melted frost decreased after installing trays.

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ABSTRACT

When the surface temperature of the outdoor coil in an air source heat pump (ASHP) unit is lower than both freezing point of water and the air dew point, frost can be formed and accumulated over outdoor coil surface. Frosting affects the energy efficiency, and periodic defrosting therefore is necessary. Reverse cycle defrosting is currently the most widely used defrosting method. A previous related study has indicated that during reverse cycle defrosting, downwards flow of the melted frost over a multi-circuit outdoor coil could affect the defrosting performance, without however giving detailed quantitative analysis of the effects. Therefore an experimental study on the effects has been carried out and a quantitative analysis conducted using the experimental data. In this paper, the detailed description of an experimental ASHP unit which was specifically built up is firstly reported. This is followed by presenting experimental results. Result analysis and conclusions are finally given.

1. Introduction

Since the oil crisis in the early 1970s, various studies on developing higher efficiency but smaller and quieter heat pump systems have been carried out. An obvious advantage for a heat pump unit is that it provides either cooling or heating from one single apparatus without major modification [1]. ASHP units as heating and cooling source for heating, ventilation and air conditioning (HVAC) installations in buildings have been increasingly used over the recent decades in many parts of the world including China [2–4]. When, however, an ASHP unit is operated in winter, frost could be formed and accumulated on the surface of its finned outdoor coil, which is usually of multi-circuit structure in order to enhance its heat transfer and minimize its refrigerant pressure loss [5,6]. Frost deposited and accumulated over the outdoor coil surface will behave as a layer of thermal resistance between the humid ambient air and the surface, reducing heat transfer rate [7–9]. Furthermore, a frost layer reduces airflow passages and hence increases the pressure drop on air-side [10], and degrades the performances of the ASHP unit. Consequently, periodic defrosting becomes necessary.

Among several other defrosting methods currently used for ASHP units, such as electric resistance heating, hot water spray and hot refrigerant reverse cycle, reverse cycle defrost is the most widely used [11–16]. During a standard reverse cycle defrost process for an ASHP unit, its indoor coil acts as an evaporator and its outdoor coil as a condenser. While most of the melted frost drains off from the surface of outdoor coil, some may retain on the surface. The retained water should be removed so that it will not become ice again when the ASHP unit returns to the heating mode. Hence, a complete defrost process includes both frost melting and

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coil surface drying. During a defrosting process, not only a great deal of energy for melting frost and vaporizing the melted frost off outdoor coil surface is consumed, but the thermal comfort of occupants may also be adversely affected science no heating is supplied during defrosting [17]. Therefore, shortening a defrosting period should be one of the control purposes for the ASHP units. For example, Chinese Standard GB/T 7725-2004 specifies that the defrosting duration for an ASHP unit should not exceed 20% of its total working hours.

Since drying coil surface plays an important role in a reverse cycle defrosting process, the effects of the melted frost downwards flowing due to gravity on the surface of outdoor coil in an ASHP unit on its operating performances should be considered. For a multi-circuit outdoor coil of an ASHP unit, the defrosting on different circuit's surface is uneven. It was reported [12,13,18–19] that, when the top circuit ends defrosting, the bottom ones may still be covered with frost. One important reason for this is the existence of melted frost flowing from top to bottom due to gravity. However, few studies on the effects of downwards flow of the melted frost over a multi-circuit outdoor coil may be identified in open literatures, except that in a previous related study [20], it was suggested that downwards flow of the melted frost over a multi-circuit outdoor coil of an ASHP unit during reverse cycle defrosting could affect the defrosting performance, by using more energy for defrosting and prolonging a defrosting process. This is because downwards flow of melted frost helps form or reinforces a water layer between the frost and the coil surface, which introduces a thermal resistance [14], and thus reduces the heat transfer between them. However, no detailed quantitative analysis of these negative effects was carried out and thus reported.

This paper reports on an experimental study on the effects of downwards flowing of the melted frost over the surface of a five-circuit outdoor coil in an experimental ASHP unit during reverse cycle defrosting. The detailed description of the experimental ASHP unit is firstly presented. This is followed by presenting various experimental conditions and experimental results. Thirdly, a quantitatively analysis on the impacts of melted frost flowing downwards due to gravity on the heat and mass transfer process is presented. Finally, a conclusion is given.

2. Experimental work

2.1. Experimental ASHP unit

An experimental ASHP unit was established specifically for undertaking the experimental work presented in this paper. The unit was built based on a commercially available 6.5 kW heating-capacity variable speed (VS) ASHP unit. The experimental unit was placed in an existing environmental testing chamber, when there were a simulated outdoor frosting space and a simulated heated indoor space. The sizes of both spaces were 3.8 m (L) × 3.8 m (W) × 2.8 m (H). Fig. 1 shows the schematic diagrams of the ASHP unit installed in the environmental testing chamber. It was a split-type unit made of a swing type compressor, an accumulator, an electronic expansion valve, a four-way valve, an outdoor coil and an indoor coil. The outdoor coil was specially designed for this study, as shown in Fig. 2. There were five individual and parallel refrigerant circuits and the airside surface area for each circuit was equal. The outdoor coil was vertically installed and in each circuit a solenoid valve and a stop valve were used.

Five water collecting trays made of PVC which can be placed under each circuit of the outdoor coil when needed have been added to the outdoor unit. In this way, the flowing of melted frost would be restricted within a circuit and could not flow to the surfaces of other circuits underneath. Furthermore, five water collecting cylinders were connected to these trays, so that the melted frost from each circuit during defrost may be collected and weighed. The specifications for the five-parallel refrigerant circuit outdoor coil are shown in Table 1.

There was a separate air conditioning system in the environmental testing chamber, and sensible and latent load generating units (LGUs) which were used to simulate test thermal load, so that suitable experimental conditions in both outdoor and indoor spaces can be maintained. During normal frosting (or heating) operation, the outdoor frosting space was maintained by operating the LGUs and experimental ASHP unit together, and indoor heated environment by the existing air conditioning system and the experimental ASHP unit.

Fig. 3 shows the details of the airside of outdoor coil in the experimental ASHP unit placed in the frosting outdoor space. On the windward side, air dry bulb temperatures were measured at 10 points using thermocouples (Type K, of ±0.1 °C accuracy) and air wet bulb temperatures at 5 points using temperature sensors (PT100, class A). The average values from these measurements were taken as the inlet air dry bulb temperature and wet bulb temperature in the follow-up calculation. On the other hand, air parameters of temperature and humidity exiting the outdoor coil were measured using a hygrosensor (±0.2 °C and ±1.0% RH accuracy) located inside an air duct 900 mm away from the outlet of outdoor coil.

To ensure the best possible accuracy of measurement, the air wet bulb temperature sensors positioned on the windward side of the outdoor coil were calibrated using the hygrosensor. Moreover, outdoor coil air flow rate was measured by using a flow hood (of ±3% accuracy) having a 16-point velocity grid located at the center of a 400 × 400 mm air duct of 600 mm long, as shown in Fig. 3.

The temperatures of tube/coil and fin surfaces of outdoor coil were measured using K-type thermocouples. Ten were for measuring the refrigerant tube surface temperatures at both the entrance and exit of the five refrigerant circuits. Five were affixed on the fin surface at the center of each circuit. Furthermore, five more thermocouples were placed inside the cylinders for measuring the temperatures of melted frost collected. In addition, pressure transmitters having an accuracy of ±0.3% of the full scale reading were used to measure refrigerant pressures. The mass flow rate of refrigerant was measured by a variable-area flow meter with an accuracy of ±1.6% of the full scale reading. For all sensors/measuring devices, they can output direct current signal of 4–20 mA or 1–5 V. In addition, during defrosting, photos were taken at an interval of 10 s for visually recording the conditions of frost melting on the surface of outdoor coil.

2.2. Experimental conditions and procedures

Prior to defrosting operation, the experimental ASHP unit was in operation at frosting (heating) mode for 1 h, at the frosting ambient temperature of 0.5 ± 0.2 °C (dry-bulb temperature) and 90 ± 3% RH. This was achieved by the joint use of both the LGUs and experimental ASHP unit placed in the outdoor frosting space.

Before starting defrost, the compressor was turned off first. Then after one minute, the four-way valve was changed to defrost mode. Four seconds later, the compressor was switched on again, and thus a defrost operation was commenced. Defrost operation was ended manually when the temperature of tube surface at the exit of the lowest refrigerant circuit of the outdoor coil arrived at 24 °C [17,21–26]. The outdoor air fan was switched off during defrosting, but the indoor air fan remained operation at a lower speed. During frosting, the air temperature in heated indoor space was kept at 20 °C. This was achieved by the joint use of both the