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Local frosting behavior of a plated-fin and tube heat exchanger according to the refrigerant flow direction and surface treatment

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ABSTRACT

Heat pumps have been promoted as energy-efficient heating and cooling systems. However, in the heating mode, heat pump performance is often significantly degraded by the frost layer that forms on the fin surface of the heat exchanger due to the low temperature of the outdoor unit. In this research, we experimentally investigated the thermal performance and frosting behavior at various locations on a plate-fin and tube heat exchanger with respect to refrigerant flow direction (counter-flow and parallel-flow) and fin surface treatment (bare, hydrophilic, hydrophobic, and hybrid). On the bare heat exchanger, the frost growth was more uniform with a counter-flow than with a parallel-flow, and thus the overall heat transfer rate was higher under counter-flow condition. The performance difference between the counter-flow and parallel-flow conditions became more significant when the heat exchanger was operated at lower refrigerant temperature and air velocity. Although the initial heat transfer rate of the hydrophilic unit was the highest among the surface-treated heat exchangers, this unit also suffered a dramatic reduction in the heat transfer rate because of the fast frost growth and non-uniform frosting behavior on its rear side. On the other hand, although the hydrophobic heat exchanger had a slightly lower initial heat transfer rate than the hydrophilic unit, it exhibited a consistent heat transfer rate throughout the experiment, owing to the frost retardation effect and the relatively uniform frosting behavior on its rear side. Each of the hybrid hydrophilic–hydrophobic surface-treated heat exchangers showed a lesser reduction of the heat transfer rate than the hydrophilic unit, and a higher initial heat transfer rate than the hydrophobic unit.

1. Introduction

The demand for heat pumps continues to increase because they are more energy-efficient than other heating and cooling systems. Since heat pumps are designed primarily for cooling, they are normally operated under counter-flow condition, which are more efficient for cooling, and are run using a reverse cycle under parallel-flow condition when used for heating. In the latter circumstances, the fin surface temperature of the outdoor unit is low, and frost forms when humid air contacts the surface. The frost layer blocks the air passages of the heat exchanger and creates additional thermal resistance, causing performance degradation. Therefore, detailed knowledge of the frost growth at various locations on a heat exchanger is important for improving its thermal performance.

There have been a few studies of frost formation according to refrigerant flow direction. Aoki et al. [1] conducted frosting experiments on a flat plate under both counter-flow and parallel-flow conditions, and compared the properties of the frost layer in the upstream and downstream regions of the plate. Nelson [2] used numerical calculations to design a liquid overfeed system, and studied its efficiency under counter-flow and parallel-flow conditions. Aljuwayhel et al. [3] investigated the air-side and refrigerant-side temperatures and the efficiency of a liquid overfeed heat exchanger under counter-flow and parallel-flow conditions, using both numerical and experimental techniques. The authors of the latter two studies reported that a parallel-flow arrangement yields better efficiency. However, the subject of [1] was a flat plate rather than a heat exchanger, while [2,3] focused on liquid overfeed systems rather than air-source heat pumps. Liquid overfeed heat exchangers have different temperature characteristics between the air and refrigerant with respect to the airflow direction compared to the heat exchangers used for air-source heat pumps.

Frost retardation and improvement of condensate water draining for heat exchangers can be achieved via fin surface treatments, thereby improving their thermal performance. The following studies examined the performance of surface-treated heat exchangers under frosting conditions. Jhee et al. [4] investigated the effect of surface treatments on a heat exchanger used for refrigerators,

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Nomenclature

B.C	base conditions
BR_{ave}	average blocking ratio (%)
c_p	specific heat of air (kJ/kg k)
F-S	fin-side (Fig. 2)
L_H	latent heat of sublimation (kJ/kg)
$\dot{m}_a$	mass flow rate of air (kg/s)
$\triangle P_a$	air-side pressure drop (Pa)
$\dot{Q}_t$	heat transfer rate (kW)
T	temperature (°C)
T-S	tube-side (Fig. 2)
t	operating time (min)
$u_{a,ini}$	initial air velocity (m/s)
w_a	absolute humidity (g/kg$_a$)

Greek symbols

θ_s	static contact angle (°)

Subscripts

a	air
ave	average
def	defrosting
f	frosting
in	inlet
ini	initial
lat	latent heat
out	outlet
sen	sensible heat transfer

and reported that the hydrophilic unit exhibited 20% better drainage of the remained (residual) water than the bare unit. Huang et al. [5] carried out frosting experiments with a surface-coated fin tube heat exchanger, and concluded that the air-side pressure drop of the coated unit was lower than that of the uncoated unit. Kim et al. [6] studied the frost growth on louvered-fin and tube heat exchangers, and observed a frost retardation effect on the hydrophobic unit. However, Jhee et al. [4] focused on surface-treated heat exchangers designed for refrigerators rather than heat pumps, and Huang et al. [5] studied only a single type of surface treatment for heat exchangers. Kim et al. [6] investigated different types of surface-treated louvered-fin and tube heat exchangers, but did not consider local frost growth behavior, which can be crucial for understanding frost-induced degradation of thermal performance in heat exchangers.

Although many research efforts have been devoted to exploring the effects of refrigerant flow direction and surface treatment on frost growth over the fin surfaces of heat exchangers, there is still a dearth of experimental studies of local frosting behavior and the resulting thermal performance of heat exchangers with respect to refrigerant flow direction and surface treatment, which would be helpful for improving the performance of air-source heat pumps. Accordingly, we investigated the characteristics of frost formation and thermal performance of plate-fin and tube heat exchangers with no surface treatment, in terms of refrigerant flow direction. We then performed frosting experiments with surface-treated heat exchangers, including hydrophilic, hydrophobic, and hybrid hydrophilic–hydrophobic units. We examined the frost growth at various locations, and studied remained water behavior according to the defrosting conditions of the heat exchangers. All of the experimental parameters used in this study were based on the operating conditions of typical air-source heat pumps.

2. Experiments

Fig. 1 shows the experimental setup for the frosting and defrosting experiments [7,8]. The setup consisted of five components: a test section, where the plate-fin and tube heat exchanger was installed; a climate chamber to maintain a constant air temperature and humidity; a refrigeration section to regulate the temperature and flow rate of the cold refrigerant for the frosting experiments; a defrosting section to supply warm refrigerant for the defrosting experiments; and a recirculation section to connect the other components and act as an air pathway. Bypass valves were installed at the inlet and outlet of the heat exchanger to alternately supply cold refrigerant for the frosting experiments and warm refrigerant for the defrosting experiments. The refrigerant used in those experiments was a solution of ethylene glycol with a mass ratio of 1:1.

Fig. 2 illustrates the plate-fin and tube heat exchanger with six steps and two rows that was used in the experiments. The length, height, and width of the heat exchanger were 36 mm, 126 mm, and 150 mm, respectively, and the fin pitch was 1.81 mm. The fin surfaces were rendered hydrophilic and hydrophobic by coating poly-acrylate resin and by coating fluorinated resin, respectively, and by subsequent drying with 300 °C hot temperature wind (Dong-il Aluminum Co.) [9]. The thickness of the coated film was less than 1.2 μm. As a result, the static contact angles of the bare, hydrophilic, and hydrophobic surfaces were $\theta_s = 75°$, $\theta_s = 3°$, and $\theta_s = 130°$, respectively. We devised and tested three additional heat exchangers with different types of hybrid hydrophilic–hydrophobic surface treatments: a dual unit [6] with a hydrophilic surface on one side of each fin and a hydrophobic surface on the other side, a hybrid hydrophilic (HPIL) unit with a hydrophilic coating on the first row of fins and a hydrophobic coating on the second row of fins, and a hybrid hydrophobic (HPOB) unit with a hydrophobic coating on the first row of fins and a hydrophilic coating on the second row of fins (opposite to the HPIL unit). The plate-fin tube heat exchangers with multiple steps are generally operating under the cross-flow condition. In order to investigate the effects of the refrigerant flow direction (i.e., the influence of the refrigerant flow inlet and the corresponding flow direction within the cross-flow condition), the frosting experiments were conducted under the cross-counter and the cross-parallel flow conditions, respectively. A rigid borescope with a 90° range of view and a 4-mm inner diameter was inserted into the test section to capture local images of the frost layer. Tiny high-quality webcams were also installed in the inlet and outlet of the test section to capture overall images of the frost layer. The captured images were analyzed with a commercial image analysis software package (NIS-D Element System, Nikon).

When a frosting experiment was finished, the pump supplying the cold refrigerant was stopped, and the frosting experiment bypass valves located at the inlet and outlet of the test section were closed. Warm refrigerant ($T_{def} = 50$ °C) was then supplied for the subsequent defrosting experiment. To prevent the remained water from scattering at the conclusion of the defrosting experiment, blocking plates were installed in the test section. The remained water was blown by compressed air into a drawer, absorbed with cotton tissues, and weighed using a digital chemical balance with an accuracy of 10^{-4} g. The uncertainties of the measured values in the paper were calculated based on the Coleman et al. [10]. The level of confidence is approximately 95%, and to obtain the accurate and reliable data, the experiments were repeated at least five times under the same experimental conditions.