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A Review on the Performance of Fin-and-Tube Heat Exchangers Under Frosting and Defrosting Conditions

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ABSTRACT: This paper reviews the literature on the performance of fin-and-tube heat exchangers under frosting and defrosting conditions. The effects of frosting and defrosting on the following parameters were discussed: frost growth, overall heat transfer coefficient, surface roughness, and surface characteristics on the heat exchanger. Comparisons of the experimental results and empirical correlations that were obtained from open literature were presented. In addition, a review of the defrosting methods was conducted.

Nomenclature

$C_{p,a}$: specific heat at constant pressure
d_F : $d_{t,o}+L_F$
$d_{t,o}$: radius of tube
f : frictional coefficient
f_0 : frictional coefficient at non-frosting condition
F_t : $(T_a-T_M)/(T_M-T_{HX,s})$
G : flow rate per unit area [lb/ft^2·hr]
h : heat transfer coefficient [W/m^{2}K]
L_F : fin height
L_H : heat of sublimation [336 kJ/kg]
P : partial pressure of water vapor [N/m^2]
Pr : Prandtl number, (ν/α)
P_{sat} : saturated vapor pressure [N/m^2]
Re : $[\rho_a V_{\max}(d_{t,o}+2X_f)]/\mu_a$
S_F : fin pitch
T : temperature [℃]
t : time [sec]
$T_{HX,s}$: heat exchanger surface temperature [K]
T_M : freezing temperature [K]
$V_{\max}$: velocity at the point of minimum air flow path
X : frost thickness [mm]
X_F : fin thickness
X_f : frost thickness

Greek symbols

μ : viscosity [kg/(m·s)]
Π : $(P-P_{sat})/(P_{sat}-P_{f,s,sat})$

Subscripts

a : air
f : frost
HX : heat exchanger

1. Introduction

A major issue of the common refrigeration equipment is the formation and growth of frost on the heat exchanger when the temperature of the coils is below freezing point. As the frost forms, it decreases airflow area due to the blockage effect of the flow passage and deteriorates heat transfer from the warm air to the cold surfaces. As a result, the heat trans-

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fer rate is reduced and the pressure drop increases. Under such conditions, the defrost process is required to maintain good performance on fin-and-tube heat exchangers. Better understanding of the formation, growth, and removal of the frost is required to enhance the performance of the heat exchanger and design the optimal unit. Up to now, most studies for the frost formation and the defrost process focused on simple geometries such as tubes, annuli, cylinders, flat plates, and parallel plates. O'Neal and Tree(1) provided a comprehensive review of frosting in those geometries. However, the studies for the majority of the actual refrigeration units which have more complex geometries such as fin-and-tube heat exchangers are limited due to the large number of variables, difficulty in quantitative analysis for the frost, and the thermodynamic properties of humid air. In this respect, the precise analysis of fin-and-tube heat exchanger performance becomes very difficult and a generalization of that is too complicated to formulate.

This paper reviews the literature on the performance of fin-and-tube heat exchangers under frosting and defrosting conditions. The objective of this paper is to provide available information on various aspects of the frosting and defrosting process for fin-and-tube heat exchangers. This paper consists of four sections: (1) frost growth, (2) overall heat transfer coefficient, (3) surface roughness, and (4) surface characteristics on heat exchanger. Besides, because there is negative effect of the frost in fin-tube heat exchangers, the accumulated frost must be removed from the heat exchanger surface on either a continuous or intermittent basis. This paper includes the introduction of the defrosting methods found in literature.

2. Frost growth

Frost properties are very important to build an analytical model of frost growth. Density and thermal conductivity which affect the heat and mass transfer under frosting have an inter-relation and are known to be the function of air velocity, cold plate temperature, and air humidity. Reid et al.(2) found that frost density increased as the air approached the cold plate by vapor diffusion and high frost density was developed when the air humidity became low and air velocity was fast from the experiment using liquid nitrogen. Generally, frost growth rate increases as the surface temperature of the cold plate decreases and air humidity increases. However, the influence of air velocity on frosting is not conclusive.

Schneider(3) insisted that frost growth rate have nothing to do with Re, but O'Neal,(1) Kamei et al.(4) and Yamakawa et al.(5) had different opinions that it is greatly influenced by Reynolds number, especially between 12,000~18,000. Although frost growth along the location of fin-and-tube heat exchanger has not been explained completely, Hayashi(6) and Niederer(7) presented that the amount of frosting became large at the entrance of air flow as observed by previous investigators. However, Betty et al.(8) reported that the location had nothing to do with frost growth and O'Neal(1) demonstrated that the frost thickness was influenced only when Re was less than 10,000, not when over 10,000 along the heat exchanger's location.

Many investigators presented the frost growth model considering the components affecting the frost growth. Schneider(3) simulated the frost thickness (X_f) from the balance between heat transfer rate of vapor diffusion on the frost surface and that of the thermal conductivity between the frost layers using Eq. (1). He mentioned that Re and vapor pressure difference between air and the frost surface were irrelevant with the frost growth.

$$X_f = 0.465\left(\frac{k_{ice}}{L_H}\rho_{ice}\right)^{0.5} \times T_a^{0.47}(T_f - T_{HX})^{0.49}\Pi^{0.25}F_t \qquad (1)$$

Cremers et al.(9) presented Eq. (2) that expressed the frost thickness on perpendicular tube under free convection condition as a function of time (t), tube surface temperature ($T_{HX,s}$), and frost surface temperature ($T_{f,s}$) to help understanding of the complicated geometry.

$$X_f = 0.12[t(T_{f,s} - T_{HX,s})]^{0.43} \qquad (2)$$

3. Overall heat transfer coefficient

The overall heat transfer coefficient, U_o, is an important heat transfer parameter. The thermal resistance of the system is the inverse of the product (U_oA). Therefore, a knowledge and understanding of its variation and trends under frosting conditions is important. If U_o is low, then it means that the system has a high thermal resistance. Hosoda and Uzahashi(10) showed that the heat transfer coefficient dropped as much as 20% for frost thickness of 3 mm as the frost formed and grew. The heat transfer coefficient was not only a function of the frost thickness but also a function of the geometry, the frost properties, and the flow rate of the air flowing across the coils. As such, the complexity of the problem is apparent.

Barrow(11) demonstrated the following results after the analysis of the frosting performance on heat and mass transfer for fin-and-tube heat exchangers. Compared to the effect of heat and mass transfer from blocking the air flow path due to frost growth, the insulation effect of the frost layers was small and the overall heat transfer coefficient was a function of frost thickness, frost properties, and air velocity.

Stoecker(12) tested fin-and-tube heat exchangers on forced convection with constant air flow and frosting conditions. He reported U_o's variation according to the frost growth based on the log mean temperature difference (LMTD) method between air and refrigerant at non-frosting conditions. Compared to non-frosting conditions, U_o increased as much as 5~6% for accumulated frost amount of 0.9 kg. As the frosting conditions were lasting, and eventually the value of U_o had a tendency to decrease. He explained that there was an initial increase in U_o with the onset of frosting as a result of increasing surface roughness which had an effect on an increase in heat transfer area and air flow velocity. Besides, the trend of decreasing in U_o as frosting proceeded was a result of the insulating effect of the frost as the frost layer grew. He further observed that an increased air flow rate compensated the increase in U_o. Under consideration of the effect of fin pitch on fin-and-tube heat exchangers, U_o for large fin pitch (4 fins per inch) was higher than that for small fin pitch (9 fins per inch). He investigated that despite the same size of two coils with the same capacity under non-frosting condition, a heat exchanger with large fin pitch was more efficient as frosting proceeded.

Chen et al.(13) presented that U_o was enhanced due to an increase of surface roughness on the frost layers with the onset of frosting and heat transfer coefficient was expressed as a function of surface roughness as given below.

$$\frac{h}{C_{p,a}G} = \frac{0.5f}{1+1.5\mathrm{Re}^{-1/2}\mathrm{Pr}^{-1/6}(\mathrm{Pr}\cdot f/f_o - 1)} \qquad (3)$$

Al-Sahaf(14) compared the measured frosting data with the numerical analysis for the tubular configurations to understand the most important factor under frosting conditions. Then, he developed theoretical modeling of thermal performance of fin-and-tube heat exchangers under the actual conditions in which frost layers made air flow rate decrease. He examined thermal performance from the experiments by changing various configuration factors on fin-and-tube heat exchangers, such as fin pitch, tube diameter, number of tube. He used the enthalpy difference between inlet and outlet of coils to analyze the heat transfer rate. Theoretical approach to analyze fin-and-tube heat exchanger performance was extended to whole heat exchanger after analyzing thermal performance of divided fin and tube heat exchanger into many components. He presented a heat transfer correlation considering frost thickness effect under frosting conditions by modifying the Briggs and Young correlation.(15)

$$h_a=\left[\frac{k_a}{d_{t,0}+2X_f}\right] \cdot 0.134\mathrm{Re}^{0.681}\mathrm{Pr}^{0.33}\left[\frac{S_F-(X_F+2X_f)}{d_F-d_{t,o}}\right]^{0.2} \cdot \left[\frac{S_F-(X_F+2X_f)}{X_F-2X_f}\right]^{0.1134} \quad (4)$$

4. Surface roughness

The random nature of the deposition of the frost results in the frost surface being rough and uneven. The roughness of the frost surface is usually difficult to predict. However, the roughness of the surface contributes to an enhancement of the heat transfer to fin-and-tube heat exchanger.

Hayashi et al.(6) examined the effect of mass transfer in turbulent flow as a result of surface roughness through the experiment and numerical simulation. They noted rapid deposition of the frost with the onset of frosting resulted in turbulent flow due to surface roughness. According to their frosting model, although surface roughness increased with the onset of frosting, the frost deposition increased because of active heat transfer from turbulent flow between frost columns on frost layers as surface roughness increased. When the frost was somewhat deposited, the effect of surface roughness became relatively smaller as compared with that of the frost thickness and mass transfer rate converged constant value.

Gatchilov and Ivanova(16) found that the roughness was also a function of the geometric parameters. They investigated the effect of heat transfer performance along with the changes of the design factors and operating factors, which resulted in the experiments of three different heat exchangers with 16 mm diameter copper tube, tube space in the direction of air flow, tube space in the vertical direction of air flow, and fin pitches of 7.5, 10, and 15 mm. They found that for a small increase in relative humidity and a large increase in flow velocity, the surface roughness increased considerably. Since frost thickness was extremely high at the initial row, fin pitch was the most important factor in the design of fin-and-tube heat exchangers.

Considering that the surface roughness is helpful to the performance of the heat exchanger only for the initial part of the frosting process, and that quantification is very difficult, it is natural that very few investigators have attempted to study the roughness effects on frost formation in detail.

5. Surface characteristic on heat exchanger

Many investigators have different opinions on the effects of surface characteristics on fin-and-tube heat exchangers. Saito et al.(17) noted that hydrophobic surface weakened frost formation and adhesion. Seki et al.(18) studied that the frost formation on hydrophilic surface was faster than that of hydrophobic surface. Tasuda et al.(19) also found that a heat exchanger which included super-hydrophobic surface with 160 degree of contact angle prolonged operating time. On the other hand, O'Neal et al.(20) reported that heat exchangers of hydrophilic surface had more excellent performance than that of hydrophobic surface. Östin et al.(21) reported that hydrophilic surface made the frost formation retarded from the experiments which had applied hydrophilic and hydrophobic property on heat exchangers using polymer.

6. Defrost controls

Currently, in most refrigeration systems, heater type defrosting is most widely used, such as pipe heater which defrosts from heat transfer on fin, sheath heater which melts the deposited frost from natural convection by heat emission of about 300~400℃ and glass heater which uses the radiation and natural convection from the high amount of heat source over 700℃. Nevertheless, these defrosting methods have an influence on the defrosting as well as frosting conditions. For example, in case of pipe heater, the blockage effects for frosting conditions between a defrost heater and a refrigerant tube decrease the air flow rate and heat transfer rate. Therefore, many investigators have made researches in other methods to remove the frost accumulation. As a result, the defrosting can be accomplished using electric resistance heating, warm water, off-cycle (for cooler), or liquid desiccant, and hot gaseous control. However, because each method has the side effect such as the increase of the cabinet temperature and high electric power consumption, the defrost method should be considered carefully.(22)

7. Conclusions

The conclusions which can be derived from this review of the literature are as follows:

(1) Frost formation and growth were known to be the function of flow velocity, relative humidity and surface temperature. The frost accumulation increased with the relative humidity and flow velocity of the air flowing across the heat exchangers. However, the lower the surface temperature was below freezing point, the more the amount of frost deposition was.

(2) The overall heat transfer coefficient had an initial increase with the onset of frosting as a result of increased surface area and surface roughness. This increase was soon offset by the increase in thermal resistance of the frost layer.

(3) Surface roughness was helpful to fin-and-tube heat exchanger performance only in the early stages of frost growth. It was a function of the relative humidity and air flow rate flowing across the coils.

(4) Further studies are recommended to study the effect of surface treating, such as hydrophilic and hydrophobic for frost formation and adhesion.

(5) Several methods were used to remove the frost deposition, such as defrost heaters, warm water, off-cycle, a liquid desiccant and hot gas defrosting.

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