Theoretical study on the critical heat and mass transfer characteristics of a frosting tube


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HIGHLIGHTS

- Critical and Neutral Frost Thickness, CFT and NFT were presented for a frosting tube.
- CFT: Before which, the frost layer enhances the heat transfer rather than depress it.
- NFT: Before which, the frost layer does not execute negative impact on heat transfer.
- The values of CFT and NFT are concluded to be impacted by five parameters.
- By sensitivity analysis, the main factors to impact the CFT and NFT were discussed.

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ABSTRACT

A theoretical study was conducted to investigate the critical heat and mass transfer characteristics on a frosting tube. The parameters, Critical Frost Thickness (CFT) and Neutral Frost Thickness (NFT) were presented for the first time. The heat transfer was found to increase before the point CFT, and decrease to the initial value of a non-frosted tube at the point NFT. The findings provide a reasonable explanation for the heat transfer increase for a fin-tube heat exchanger at the early stages of frost formation. By theoretical study, the values of CFT and NFT were impacted by the following five parameters, the air temperature $T_a$, humidity $\phi$, velocity $V$, tube wall temperature $T_w$ and tube outside diameter $d_2$. The influences of these parameters on the CFT and NFT were further discussed. By sensitivity analysis, the CFT and NFT were found to be more sensitive to the parameters of $\phi$, $V$ and $d_2$.

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1. Introduction

Condensation on the heat exchanger surface occurs when the temperature of that surface below the dew point of the ambient moist air. If this temperature is below 0 °C, the condensate freezes and a layer of frost forms on the surface. Frost accumulation on heat exchangers usually causes a series of negative problems, such as a reduction in both the capacity and efficiency of a refrigeration system, and excess energy consumption due to defrost. The experimental results of Wang [1] indicated that the frosting process could reduce the heating capacity of the air source heat pump by 29%. The cooling capacity of air coolers operating under frosting conditions could be reduced by about 35% according to the findings of Sanders [2]. To reduce the trouble caused by frost deposition, numerous researchers have investigated the problems related to frosting issues in the past decades. Among these studies, an interesting phenomenon is found that the heat transfer capacity of the coil increases but not decreases at the early stages of frost formation. The reason of this initial increase has been widely discussed. Stoecker [3] and Lotz [4] attributed this initial increase to the extended area afforded by the initial growth of ice crystals or the increase in air velocity over the surface due to the decreased passage area. Rite and Crawford [5] proposed three reasons for this initial increase. First, the frost could fill in the gaps between the tube and fins, thus decreasing the contact resistance between the tube and fin. Second, the roughness of the frost could promote turbulent flow, which had a better heat transfer coefficient than laminar flow. Finally, they believed the frost can act as another extended surface. The addition of microscopic surface area increased the heat transfer capacity of the coil. Carlson [6] also considered the initial increase of overall heat transfer coefficient be caused by the increased fin efficiency. Though above analyses are reasonable, they are still in the stage of assumption due to lack of the theoretical or experimental validation. Some other reasons may
also contribute to the initial increase of heat transfer for a frosted heat exchanger. This paper tries to specify the contribution of the heat transfer increase from the tube side.

While frost forms and grows up on a tube, it works like a moving insulating layer outside of the tube. According to the research of Porter [7], heat loss of a long cylinder with small radius would increase rather than decrease, when a small amount of thermal insulation is added. This means an adverse effect is resulted due to the use of insulation material. It is a special characteristic for the cylinder type heat exchanger. Lewins and Cockerill [8] indicate that the critical radius of an insulated duct is \( \lambda/h_{\text{bo}} \), where \( \lambda \) is the heat conductivity coefficient of insulated material and \( h_{\text{bo}} \) is the ambient heat convective coefficient. This result has been commonly mentioned in textbooks of heat transfer, Bejan A. [9], Incropera F.P. [10], Holman J.P. [11], Mills A.F. [12] and Kreith F. [13] Wong et al. have conducted plenty of researches related to this critical heat transfer phenomenon of an insulated duct. In their studies, they proposed different theoretical models, like plane wedge thermal resistance (PWRT) model [14] for regular pipe, square top solid wedge thermal resistance (SSWRT) model [15] for cubic pipe, and regular polygon top solid wedge thermal resistance (RPSWT) model [16] for regular polyhedral pipe. They also studied the characteristics of critical and neutral thicknesses of an insulated oval duct by using two-dimensional numerical analysis and the one-dimensional PWTR model [17].

The most concern of this work is the critical heat and mass transfer characteristics of a frosting tube. The existence of Critical Frost Thickness (CFT) and the Neutral Frost Thickness (NFT) on a frosting tube is validated theoretically. This result can serve as one of the concrete interpretations to the foregoing issue, why the initial increase of heat transfer capacity for a frosting heat exchanger exists? Though similar results are found to the traditional insulated tube, the critical heat transfer of a frosting tube is a transient phenomenon along with a mass transfer process. According to the study of C.M. Robinson and A.M. Jacobi [18], the frost formation and growth is a highly random process, the CFT and NFT are influenced by multi-parameters. It is concluded that the air temperature \( T_a \), humidity \( \phi \), velocity \( V \), tube wall temperature \( T_w \) and tube diameter \( d_2 \) execute dominant impacts on this process. The influences of these parameters on the CFT and NFT are further discussed in this paper. By sensitivity analysis, the actions of these parameters on the CFT and NFT are identified quantitatively.

### 2. CFT and NFT

Fig.1 shows the physical model of a frosted tube. The inside and outside diameters of the tube are \( d_1 \) and \( d_2 \). The thickness of the frost layer is \( \delta_f \) and the total diameter of this frosted tube is \( d_k \). Heat conductive coefficients of the tube wall and frost layer are \( \lambda_w \) and \( \lambda_f \). The refrigerant and air side heat convective coefficients are \( h_i \) and \( h_o \). Three parameters are applied to describe the ambient conditions, air velocity \( V \), air temperature \( T_a \) and relative humidity \( \phi \).

The heat transfer of this case is a common model, which consists of three parts, convective heat transfer between refrigerant and internal tube wall, conductive heat transfer along the tube wall, and convective heat transfer between frost surface and ambient air. Based on the heat transfer theory of a multi-layer cylinder wall, the total thermal resistance of this process can be obtained:

\[
R_{\text{tot}} = \frac{1}{h_i\pi d_1} + \frac{1}{2\pi \lambda_w} \ln \frac{d_2}{d_1} + \frac{1}{2\pi \lambda_f} \ln \frac{d_k}{d_2} + \frac{1}{h_o\pi d_k}
\]

(1)

Similarly, the total thermal resistance \( R_0 \) of a non-frosted tube can be presented:

\[
R_0 = \frac{1}{h_i\pi d_1} + \frac{1}{2\pi \lambda_w} \ln \frac{d_2}{d_1} + \frac{1}{h_o\pi d_2}
\]

(2)

Correspondingly, the heat flux in the cases with or without frost can be obtained:

\[
Q = \frac{h_i V}{2\pi \lambda_w} \left( d_2 - d_1 \right) + \frac{h_o V}{2\pi \lambda_f} \left( d_k - d_2 \right) + V \left( T_w - T_a \right)
\]

(3)

\[
Q_0 = \frac{h_i V}{2\pi \lambda_w} \left( d_2 - d_1 \right) + \frac{h_o V}{2\pi \lambda_f} \left( d_2 - d_1 \right) + V \left( T_w - T_a \right)
\]

(4)

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>( T )</td>
<td>temperature (K)</td>
</tr>
<tr>
<td>( c_{p,a} )</td>
<td>specific heat at constant pressure (kJ kg(^{-1}) K(^{-1}))</td>
</tr>
<tr>
<td>( d )</td>
<td>diameter (m)</td>
</tr>
<tr>
<td>( R )</td>
<td>thermal resistance (m(^2) K W(^{-1}))</td>
</tr>
<tr>
<td>( V )</td>
<td>air velocity (m s(^{-1}))</td>
</tr>
<tr>
<td>( Le )</td>
<td>Lewis number</td>
</tr>
<tr>
<td>( Q )</td>
<td>heat flux (W m(^{-2}))</td>
</tr>
<tr>
<td>( w )</td>
<td>absolute humidity (kg kg(^{-1}))</td>
</tr>
<tr>
<td>( L_h )</td>
<td>latent heat of sublimation (kJ kg(^{-1}))</td>
</tr>
<tr>
<td>( h )</td>
<td>convective heat transfer coefficient (W m(^{-2}) K(^{-1}))</td>
</tr>
<tr>
<td>( h_d )</td>
<td>mass transfer coefficient (m s(^{-1}))</td>
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<tr>
<td>( Re )</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>( Fo )</td>
<td>Fourier number</td>
</tr>
<tr>
<td>( t )</td>
<td>time (s)</td>
</tr>
</tbody>
</table>

### Greek symbols

| \( \xi \) | moisture absorption coefficient |

### Superscript

* | dimensionless |

### Subscripts

a | air |

| sen | sensible |
| r | refrigerant |
| f | frost |
| c | critical |
| n | neutral |
| w | tube wall |
| \( \tau_p \) | triple point of water |
\[
Q_f = \frac{T_a - T_r}{R_{\text{tot}}} = \frac{T_a - T_r}{h_a \pi d_1 + \frac{1}{2} \pi \lambda_f \ln d_2 + \frac{1}{2} \pi \lambda_f d_2 + \frac{1}{h_a \pi d_x}}
\]

(3)

\[
Q_0 = \frac{T_a - T_r}{R_0} = \frac{T_a - T_r}{h_a \pi d_1 + \frac{1}{2} \pi \lambda_f \ln d_2 + \frac{1}{h_a \pi d_x}}
\]

(4)

For Eq. (1), the first differential of \( R_{\text{tot}} \) with respect to \( d_x \) is expressed:

\[
dR_{\text{tot}} = \frac{1}{\pi d_x} \left( 1 - \frac{\lambda_f d_1}{h_a} \right)
\]

(5)

The heat conductive coefficient of frost layer \( \lambda_f \) is a variable to \( d_x \). However, it is reasonable and acceptable to assume that the frost density on the frost growth direction is uniform. According to the study of Lee et al. [19], the heat conductive coefficient \( \lambda_f \) is always a single valued function to the frost density \( \rho_f \). Therefore, the heat conductive coefficient of frost layer is considered to be uniform in the \( d_x \) direction in this study. And the first differential of \( R_{\text{tot}} \) with respect to \( d_x \) is not considered in Eq. (5).

To get the critical point of \( R_{\text{tot}} \) in the domain of \( d_x \), let \( dR_{\text{tot}}/dd_x = 0 \), the corresponding value of \( d_x \) can be obtained:

\[
d_x = \frac{2 \lambda_f}{h_a}
\]

(6)

This point can be determined as a critical point for the \( R_{\text{tot}} \). To decide whether this point is a local maximum or minimum, the second differential of \( R_{\text{tot}} \) with respect to \( d_x \) is required:

\[
d^2R_{\text{tot}} = \frac{1}{8 \pi \lambda_f} > 0
\]

(7)

Then, at the critical point \( d_x = \frac{2 \lambda_f}{h_a} \).

Based on the mathematical extreme value theory, the extreme value of function \( R_{\text{tot}} \) at the point \( d_x = \frac{2 \lambda_f}{h_a} \) is a critical minimum value. At this point, the total diameter of a frosted tube is called critical diameter, and frost thickness is called Critical Frost Thickness (CFT), which are expressed as:

\[
d_c = d_x = \frac{2 \lambda_f}{h_a}
\]

(9)

\[
\delta_c = \frac{d_c - d_2}{2} = \frac{\lambda_f}{h_a} \frac{d_2}{2}
\]

(10)

Based on the mathematical knowledge, the variation patterns of the total thermal resistance and heat flux with the growing of the frost thickness are presented in Fig. 2. In the non-frost condition, the total thermal resistance \( R_{\text{tot}} \) and heat flux \( Q_f \) are equal to the value \( R_0 \) and \( Q_0 \). Once the frost forms and grows up, the total thermal resistance \( R_{\text{tot}} \) decreases at the initial stage, and reaches the minimum when the frost gets the point CFT. After this inflexion, it increases with the growth of frost, and then another important point, Neutral Frost Thickness (NFT), appears. At this point, both the \( R_{\text{tot}} \) and \( Q_f \) return to the initial value \( R_0 \) and \( Q_0 \). The outside diameter of a frosted tube at this point is defined as \( d_x \). The value of NFT can be obtained by setting \( R_0 = R_{\text{tot}} \), combining Eqs. (1) and (2):
characteristics of a frosting tube. Therefore, large amounts work relating to the CFT and NFT are required.

3. Influence parameters for CFT and NFT

As stated above, the critical heat and mass transfer phenomenon is influenced by the frosting process, which is closely linked to the ambient conditions. In this section, the parameters that impact the CFT and NFT are specified.

The followings are the assumptions to simplify the work:

1. The distribution of frost outside of the tube is uniform.
2. The frost density on the frost growth direction is uniform.
3. The frost thermal conductivity is the function of density.

From Eqs. (9)–(12), both the CFT and NFT are functions of frost thermal conductivity \( \lambda_f \), air side convective heat transfer coefficient \( h_a \) and the outside diameter \( d_2 \). This result indicates that CFT and NFT are more apt to be built in the conditions of small dimension tube, low convective heat transfer coefficient and high frost thermal conductivity. However, the later two parameters have strong relations with some other parameters.

First, it is widely accepted that the frost thermal conductivity \( \lambda_f \) is a function of frost density \( \rho_f \), which is proposed by Lee et al. [19]:

\[
\lambda_f = 0.132 + 3.13 \times 10^{-4} \rho_f + 1.6 \times 10^{-7} \rho_f^2
\]

(13)

According to the research of Jung-So Kim [20], the frost density \( \rho_f \) is influenced by multi-parameters, like Reynolds number \( Re \), Fourier number \( F_o \), air humidity \( w_o \) and dimensionless temperature \( T_a \) and \( T_w \), which can be expressed as:

\[
\rho_f = \rho_{ice} \times 4.264 \\
\times 10^{-4} (Re)^{0.346} (F_o)^{0.208} (w_o)^{-0.398} (T_a)^{14.001} (T_w)^{4.678}
\]

(14)

where,

\[
T_a = \frac{T_a}{T_p} \quad \text{and} \quad T_w = \frac{T_w}{T_p}
\]

(15)

\( T_p \) is the triple point of water.

Second, the convective heat transfer from air to the frost surface includes sensible heat and latent heat in frosting conditions, which is:

\[
q_{tot} = q_{sen} + q_{lat}
\]

\[
= h \left( T_a - T_f \right) + h_d \rho_d \left( w_a - w_f \right) L_h
\]

\[
= h \left( 1 + \frac{L_h}{C_p a Le^{0.75}} \frac{w_a - w_f}{T_a - T_f} \right) \left( T_a - T_f \right)
\]

(16)

The convective heat transfer coefficient \( h_a \) under this frosting condition is:

\[
h_a = h \left( 1 + \frac{L_h}{C_p a Le^{0.75}} \frac{w_a - w_f}{T_a - T_f} \right) = h^* \]

(17)

where, \( \xi \) is the moisture absorption coefficient, and \( h \) is the air side convective heat transfer coefficient in dry conditions, which can be calculated by James P. Hartnett [21]:

\[
h_h = 0.88 C r e^{0.16 a \rho a} d_2
\]

(18)

where, \( C \) and \( n \) are coefficients relevant to the Reynolds number \( Re \). In this study, the value of \( Re \) is less than 1000, so, \( C \) and \( n \) is set as 0.51 and 0.5 referencing James P. Hartnett [21].

The frost surface temperature \( T_f \) in Eq. (17) can also be determined by the dimensionless correlations proposed by Jung-So Kim [20]:

\[
T_f = \frac{T_f - T_{tp}}{T_a - T_{tp}} = \frac{T_w - T_{tp}}{T_w - T_{tp}} = \frac{T_a - T_{tp}}{T_a - T_{tp}}
\]

\[
+ 7.320 Re^{0.312} F_{o}^{0.314} w_o^{1.337} \left( T_a \right)^{-12.98} \left( T_w \right)^{-0.8021}
\]

(19)

Based on the Eqs. (9)–(19), the value of CFT and NFT can be achieved. From these correlations, it can be concluded that CFT and NFT are primarily influenced by five parameters, including air temperature \( T_a \), air relative humidity \( \phi \), air velocity \( V \), cold wall temperature \( T_w \) and tube outside diameter \( d_2 \). This rule can be expressed as:

\[
\text{CFT} = f_1(T_a, \phi, V, T_w, d_2) \quad \text{(20)}
\]

\[
\text{NFT} = f_2(T_a, \phi, V, T_w, d_2) \quad \text{(21)}
\]

The above conclusion indicates that unlike the traditional critical heat transfer of an insulated tube, the CFT and NFT for a frosting tube are not constant values. They may vary with time or environment conditions and behave in a highly random and transient way. The values of CFT and NFT can be only predicted under certain conditions for a given tube. Moreover, it is revealed that the CFT and NFT has a strong relation to the air side parameters and the dimension of the tube, the refrigerant side properties do not have much impact on them. It should be noted that the correlations (13) to (19) are cited from the open literature, which have been validated by either the experiments data or theoretical study. So, the conclusions drawn in this study is quite convincible.

4. Results and discussion

4.1. Case study on CFT and NFT

As shown in Table 1, the CFT and NFT are calculated from nine groups of different conditions in the range of air temperature \( 3 \text{°C} \sim 5 \text{°C} \), relative humidity \( 60\% \text{ RH} \) to \( 80\% \text{ RH} \), air velocity \( 0.5 \text{ m s}^{-1} \) to \( 0.8 \text{ m s}^{-1} \), tube wall temperature \( -25 \text{ °C} \) to \( 20 \text{ °C} \) and tube outside diameter \( 10 \text{ mm} \). The calculated results of \( Q_f/Q_0 \) varying with the frosting process under above conditions are shown in Fig.3 (a), (b) and (c). For each condition, the values of CFT and NFT are marked by red points. These results clearly illustrate the critical heat and mass transfer phenomenon of the frosting tube. First, with the growth of the frost, the heat flux increases and gets the maximum at CFT point, then decreases to the initial value at the NFT point. The calculated value of NFT is nearly doubled to

Table 1

<table>
<thead>
<tr>
<th>CFT and NFT in nine groups of different conditions.</th>
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<tbody>
<tr>
<td>Group</td>
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<tr>
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</tr>
<tr>
<td>G1</td>
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<td>G2</td>
</tr>
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<td>G4</td>
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the CFT, which means that the occurrence of NFT will be much longer than CFT in the same conditions.

To calculate the occurrence time for CFT and NFT in each condition, the dimensionless correlation of frost thickness around a frosted tube is applied, which is proposed by Jung-Soo Kim \[20\]:

\[
\frac{\delta f}{\delta_2} = 3.236(Re)^{0.04447} \left( \frac{\alpha f}{\delta_2} \right)^{0.55} \left( \frac{v_0}{\delta_2} \right)^{1.267} \left( \frac{T_w}{T_a} \right)^{-14.884} \left( \frac{T_w}{T_a} \right)^{-8.4}
\]

By using this correlation, the corresponding time of CFT and NFT, \( t_{\text{CFT}} \) and \( t_{\text{NFT}} \) can be achieved. Fig. 3 (d) shows the calculated results of \( t_{\text{CFT}} \) and \( t_{\text{NFT}} \) in each condition. The results indicate that the occurrence of CFT and NFT in each condition is varied. Although the value of NFT is nearly doubled of the CFT, the occurrence of NFT is around 4 times later than the CFT. The reason is that the frost growth rate is not always constant with time, and it may decrease step by step.

It should be pointed that the heat flux \( Q_f \) is enhanced not much at the CFT point, which can be figured out from Fig. 3. This result seems to indicate that the critical heat and mass transfer phenomenon is not so important to a frosting tube. However, another point should be noted. As stated above, the value of NFT is greater and its occurrence time is longer than CFT. In the case of G3 and G4, the NFT values are more than 2 mm, and the \( t_{\text{NFT}} \) are 62.8 min and

![Fig. 3. Heat transfer ratio varied with frost thickness.](image)

![Fig. 4. Effects of \( T_a \) and \( \varphi \) on CFT and NFT.](image)
81.6 min respectively. This means the critical heat and mass transfer phenomenon can enable the frosting tube to maintain agreeable heat transfer ability for a long period in some heavy frosting conditions. Therefore, it is still important to explore the critical heat and mass transfer characteristics of a frosting tube.

4.2. Parametric effects on CFT and NFT

In this section, CFT and NFT are calculated in a wide range of 5 influential parameters to explore how the CFT and NFT are impacted by these parameters. Fig. 4 shows the effects of air temperature $T_a$ and air relative humidity $\phi$ on the CFT and NFT. It illustrates that the CFT and NFT increase with the falling of $T_a$ and $\phi$. For example, in the condition of $T_w = -20 ^\circ C$, $V = 0.6$ m s$^{-1}$, $d_2 = 10$ mm, $\phi = 60$% RH and $T_a = 10 ^\circ C$, the calculated values of CFT and NFT are 1.2 mm and 2.7 mm. With the air temperature falling to $-5 ^\circ C$, they will rise to 1.6 mm and 4.0 mm respectively. The increases of CFT and NFT are over 33% and 48%. It also reveals that the critical heat transfer will not happen in the condition that $\phi$ is equal to 90% RH and $T_a$ is over 6.5 $^\circ C$. The reason is that the critical heat transfer is mainly influenced by the air temperature and relative humidity. A higher temperature and relative humidity can contribute to a higher moisture absorption coefficient, and then cause a greater convective heat transfer coefficient $h_w$, which has an adverse impact on the CFT and NFT.

Fig. 5 shows the effects of air velocity $V$ on the CFT and NFT. It reveals that CFT and NFT decrease rapidly with the increase of $V$. For example, in the condition of $T_a = -20 ^\circ C$, $d_2 = 10$ mm, $T_a = 4 ^\circ C$ and $\phi = 55$% RH, the CFT and NFT only exist when $V < 1.2$ m s$^{-1}$. The reason is that with the increase of air velocity $V$, the convective heat transfer coefficient also increases rapidly, which has an adverse impact on the CFT and NFT.

Fig. 6 reveals the effects of tube wall temperature $T_w$ on the CFT and NFT. It is found that CFT and NFT increase with the rise of $T_w$. For example, in the condition of $T_a = 3 ^\circ C$, $\phi = 75$, $V = 0.6$ m s$^{-1}$, $d_2 = 10$ mm and $T_w = -25 ^\circ C$, the CFT and NFT are 0.7 mm and 1.5 mm, while the tube wall temperature $T_w$ increases to $-15 ^\circ C$, they rise to 1.0 mm and 2.3 mm. The increases of CFT and NFT are over 43% and 53%. The reason is that with the rising of $T_w$, higher frost density and thermal conductivity can be achieved, which has a positive effect on CFT and NFT.

Fig. 7 shows the effects of $d_2$ on the CFT and NFT. It reveals that CFT and NFT decrease rapidly with the increase of $d_2$. For example, in the conditions of $T_a = 5 ^\circ C$, $T_w = -20 ^\circ C$, $\phi = 70$% and $V = 0.6$ m s$^{-1}$, the critical heat transfer will not happen when $d_2 > 14$ mm. In the other conditions of $T_a = 6 ^\circ C$, $T_w = -20 ^\circ C$, $\phi = 80$% and $V = 0.6$ m s$^{-1}$, the critical heat and mass transfer will not happen when $d_2 > 12$ mm. By Eq. (9), the CFT and NFT are independent to the tube outside diameter $d_2$. So, when the calculated value of $d_2$ is smaller than $d_2$, the critical heat and mass transfer will not happen. This result presents similar rules with the traditional insulated tube that the critical heat and mass transfer prefers to appear on small size tube.

By the analysis above, the critical heat and mass transfer for a frosting tube is apt to happen in the conditions of relative cold and
CFT and NFT are more sensitive to the parameters of dry ambient with lower Re number, higher wall temperature for a frosting tube and enable us to understand the transient critical heat and mass transfer process of the CFT and NFT. Though the air temperature increasing function to the parameter of which is actually a very small variation of the ambient condition. Therefore, the air temperature $T_a$ is also an un-neglectable parameter to the CFT and NFT.

5. Conclusion

A theoretical analysis of the critical heat and mass transfer characteristics of a frosting tube is conducted in this paper. Two principle points CFT and NFT are confirmed to exist during this heat and mass transfer process. The findings provide a reasonable explanation for the heat transfer increase for a fin-tube heat exchanger at the early stages of frost formation.

It is also concluded that CFT and NFT are impacted by five parameters, three of them are from air side, the air temperature $T_a$, humidity $\varphi$, velocity $V$, two are from tube side, tube wall temperature $T_w$ and tube outside diameter $d_2$, but none from the refrigerant side. The calculated results reveal that the CFT and NFT increase with the decrease of $T_w$, $V$ and $d_2$, or increase of $T_a$. By sensitivity analysis, the CFT and NFT are found to be more sensitive to the parameters $\varphi$, $V$ and $d_2$.

Nine groups of cases are studied in different ranges of above parameters. The results indicate the value of NFT is nearly doubled of the CFT, and the occurrence of NFT is around 4 times longer than the CFT. Since the occurrence of NFT is longer than CFT, the heat transfer rate of a frosting tube will not decrease in a long time, even though the tube has been covered with fairly thick frost.

The frost formation and growth is a highly random process. The findings of this paper will be validated experimentally. And the CFT and NFT for different fin-tube heat exchangers need to be specified.
These problems will be conducted and presented in the further papers.

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