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Simulation of Freezing and Defrosting Processes on Solid Surfaces

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Abstract

Freezing ice on round or flat pipe surfaces is a common challenge in refrigeration systems, including ice heat storage tanks for air conditioning systems, ice molds for tree ice machines, flake ice machines, cube ice machines, and so on. As a result, calculating and establishing the relationship between the thickness of the created rock layer and the freezing time is critical for proper arranging the heat exchange tubes, defining the size of the heat exchanger tubes, and selecting an acceptable stone mold size. This article demonstrated the simulation of the ice-freezing process on the surfaces of pipes and flat surfaces, as well as the defrosting process on those surfaces. The simulation results show that, after a freezing time of about 10 hours, the thickness of the ice layer formed on cylindrical surfaces and flat surfaces is about 50 mm and 80mm, respectively. The formation of ice on flat surfaces is better than in round one. In addition, the defrosting process is faster than the freezing process. The results also help engineers have a basis for choosing the freezing time to operate the refrigeration system safely, avoiding liquid flooding at the end of the operation process. Also, these results can be applied to ice production or ice storage for air conditioning.

Keywords: Cold storage systems, defrosting processes, freezing process, modeling, heat exchanger.

1. Introduction

In technical practice, we often encounter the freezing process of ice or other liquids on pipe surfaces or flat surfaces, for example, in ice production or ice heat storage techniques. Studying this process helps engineers obtain the necessary data to arrange a reasonable pipe design to ensure that after a certain period of freezing, the water in the tank is completely frozen. There are also cases in which, to ensure safety and convenience when defrosting, only partial freezing is required. Solving the two problems of freezing and defrosting on round and flat pipe surfaces is essential to design heat storage systems, ice mold, and many other applications as well as to arrange the structure of the refrigeration systems more appropriately and economically. Therefore, several studies have focused on this matter [1-7].

Akyurt *et al*. in [6] presented the e freezing process and the Stefan problem of ice-water systems. Four stages of freezing are identified. In pure water, fast freezing rates contributes significantly the development of numerous small ice crystals in crystal growth process. Also in this process, the temperature is nearly constant. The crystal growth time is counted from the onset of nucleation to the complete removal of latent heat. After this process, the temperature of fluid is drop. The results of this study have shown the complicated of freezing of process which is different for each kind of fluid. Thus more data on the empirical and modelling is still needed.

Rahimi *et al*. [1] investigated the initial ice formation on aluminium with surface modification. The results from this work showed that hydrophilic surfaces have a lower energy barrier for ice nucleation compared to hydrophobic surfaces, resulting in faster ice formation. The density of nucleation centers higher during the early phases of ice formation when nucleation rate is higher, which causes by the wettability of the hydrophilic surfaces. The ice density on hydrophobic surfaces is higher than on hydrophilic ones. The time evolution of ice layer morphology on substrates with varying hydrophobicity is different.

Dongo *et al*. [3] introduced an approach to detect ice formation on surfaces based on heat pulse method since the appearance of ice will affect in many domain like refrigeration, wind energy, maritime… Thus the exploitation of the thermal capacity of ice is important.

The study of Ling *et al*. [7] demonstrated numerical models to predict the growth and distribution of frost layer of microchannel louvered fin. The model was implemented in OpenFOAM. The effect of moist air inlet velocity, humidity ratio, and cold-wall surface temperature on the thickness of the local frost layer are analyzed. The frost-clogging-channel time is reduced when the cold-wall temperature and humidity ratio reduced. The results of

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this study provided a guidance for predicting the frosting of micro heat exchanger. The variation of actual conditions should be considered in design and calculation the frost layer.

From the above reviews, the process of freezing water, included the one on the outside surfaces of pipes and flat surfaces, is complicated since the ice layer thickness and density of water always changes during the process. As the thickness of the ice layer changes, thermal conductivity also changes. When the thickness of the ice layer reaches a certain level, the heat exchange process slows down significantly, and the time it takes to freeze at a certain thickness increases greatly compared to the original.

Similarly, defrosting of round and flat pipe surfaces is also encountered in cold storage systems for air conditioning. This is also a complex problem like the ice creation process. Therefore explicit models of freezinf and defrosting are needed.

In this article, we will develop the mathematical models of the freezing and defrosting process on flat and cylindrical surfaces which are the most common freezing method. These models can be used to determine and optimize the freezing and defrosting time.

2. Mathematical Model of the Freezing Process

2.1. Mathematical Model of Freezing Process on a Cylinder Surface

The process of creating ice on a cylindrical surface with known materials and dimensions is depicted in Fig. 1. The refrigerant evaporates in the tube or the refrigerant (glycol or salt water) with a deep negative temperature moves inside the tube. Cold water flowing outside the tube, is cooled and freezed to the outer surface of the tube. The thickness of the ice layer after a cooling period τ any is δ_x. Freezing time is only calculated from the moment the outside water reaches 0 ºC and begins to freeze. Hence, the problem is to establish the relationship between the thickness δ_x as the function of cooling period $f(\tau)$. During the heat exchange process, the temperature of the moving refrigerant inside the tube, t_0, is assumed to be constant.

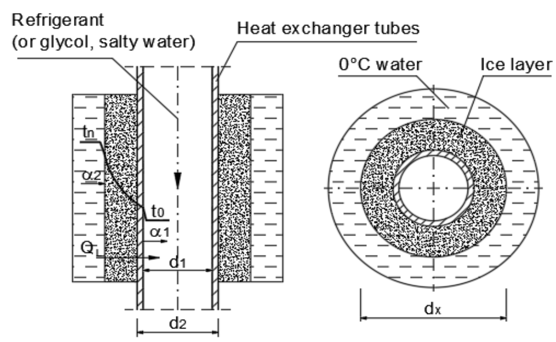

Fig. 1. Problem model

In this study, the heat transfer process from 0 ºC water to the evaporating refrigerant in the pipe or refrigerant over a pipe section of 1m is calculated, and the heat flow from is determined as follows [7, 9]:

$$Q_L = \frac{t_n - t_o}{\frac{1}{\pi(d_2+\delta_x)\alpha_2} + \frac{1}{2\pi\lambda_b} ln\frac{d_x^{tb}}{d_2} + \frac{1}{2\pi\lambda_t} ln\frac{d_2}{d_1} + \frac{1}{\pi d_1 \alpha_1}}, W/m \quad (1)$$

where t_n, t_o are temperatures of water and refrigerant, respectively, ºC;

λ_b, λ_t are thermal conductivity coefficient of tape and metal tube, W/mK ;

d_x^{tb}, d_2, d_1 are average ice layer diameter during time τ, outer and inner diameter of the refrigerant pipe, m;

α_1, α_2 are heat dissipation coefficient inside the tube and outside the ice layer, *W/m²K*.

The volume of ice stuck on 1 m of pipeline length after time τ is defined as follows:

$$m_x = \pi\rho_b(r_x^2 - r_2^2), kg/m \quad (2)$$

where ρ_b is density of ice, *kg/m³* ; r_x is radius outside the ice layer after time τ.

The amount of heat transferred to the medium in the tube after time τ is defined as:

$$Q_\tau = m_x . q_r \ , J/m \quad (3)$$

here q_r is the amount of heat needed to freeze 1 kg of ice, *J/kg*, and is determined as follows:

$$q_r = C_{pn}. t_n + r + C_{pd}. |t_d|, J/kg \quad (4)$$

where

C_{pn} is specific heat capacity of water, $C_p = 4186$ J/kgK;

C_{pd} is specific heat capacity of ice, $C_{pd} = 1800$ *J/kgK*;

r is latent heat of freezing of ice, $r = 333550$ *J/kg*;

t_n , t_d are temperature of water and ice, *ºC*.

The average capacity calculated for 1 m of pipe length during a time τ is calculated as follows:

$$Q_L = \frac{Q_\tau}{\tau} = \frac{m_x . q_r}{\tau} = \frac{\pi\rho_b(r_x^2 - r_2^2)q_r}{\tau}, W/m \quad (5)$$

The relationship between time and ice thickness can be derived based on the fomulation (1) and (5) as follows:

$$\frac{t_n - t_o}{\frac{1}{\pi(d_2+\delta_x)\alpha_2} + \frac{1}{2\pi\lambda_b} ln\frac{d_x^{tb}}{d_2} + \frac{1}{2\pi\lambda_t} ln\frac{d_2}{d_1} + \frac{1}{\pi d_1 \alpha_1}} = \frac{\pi\rho_b(r_x^2 - r_2^2)q_r}{\tau} \quad (6)$$

Then τ is determined as follows:

$$\tau = \frac{\rho_b(r_x^2 - r_2^2)q_r}{t_n - t_o} . \left[\frac{1}{(d_2+\delta_x)\alpha_2} + \frac{1}{2\lambda_b} ln\frac{d_x^{tb}}{d_2} + \frac{1}{2\lambda_t} ln\frac{d_2}{d_1} + \frac{1}{d_1\alpha_1}\right] \quad (7)$$

Substitute $r_x = r_2+\delta_x$ and $d_x^{tb} = d_2+2.\ \delta_x^{tb} = d_2+\delta_x$ into the above formula, the relationship between $\delta_x = f(\tau)$ is defined as follows:

$$\tau = \frac{\rho_b[(r_2+\delta_x)^2 - r_2^2].q_r}{t_n - t_o}\Big[\frac{1}{(d_2+\delta_x)\alpha_2} + \frac{1}{2\lambda_b} ln\frac{d_2+\delta_x}{d_2} + \frac{1}{2\lambda_t} ln\frac{d_2}{d_1} + \frac{1}{d_1\alpha_1}\Big] \quad (8)$$

Equation (8) establishes an explicit relationship between the ice freezing time and the thickness of the ice layer formed on the surface of the cylinder with size d_2/d_1. To establish the relationship in equation (8), it is necessary to know the specific thermophysical parameters of the model. The calculation results are shown in Fig. 2. The model is conducted with the thermophysical parameters of the specific problem as follows:

$\rho_b = 920\text{kg/m}^3$, $t_o = -12^o\text{C}$, $\lambda_b = 2{,}236\text{W/mK}$,

$\lambda_t = 380\text{W/mK}$, $\alpha_1 = 2500\text{W/m}^2\text{K}$, $\alpha_2 = 2200\text{W/m}^2\text{K}$.

The internal and external diameter sizes of the heat exchanger tubes are DN20(ϕ26.7/20.96), DN32(ϕ42.2/35.08), and DN50 (ϕ60.3/52.48), respectively.

The results show that when the diameter of the heat exchange tube increases, the freezing time decreases, meaning that the surface is less work and the heat exchange is better. At the end of the process, when there is already a layer of ice on the surface, the freezing time of the same thickness compared to the original will increase steeply. Thus the optimal ice thickness should be considered because the efficiency is low in this stage. The heat transfer process is prevented because the thermal resistance of the ice layer is quite large.

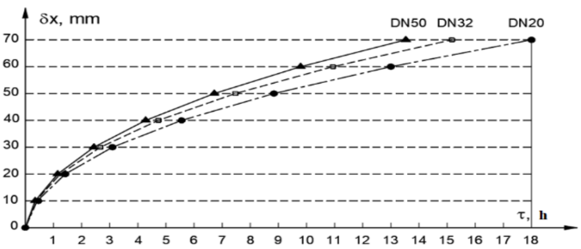

Fig. 2. Relationship $\delta x = f(\tau)$ of freezing process on steel pipe surface

2.2. Mathematical Model of Freezing Process on Flat Surface

Fig. 3 shows the process of freezing ice on a flat surface. The model usually uses salt water or glycol with a temperature of about -8 ºC to -12 ºC to cool water and freeze ice through a flat stainless steel or galvanized steel surface.

The heat flow from water to cold salt water in the tank through 1m² of flat wall area is determined according to the formula [6-8]:

$$q = \frac{t_n - t_m}{\frac{1}{\alpha_2} + \frac{\delta_x^{tb}}{\lambda_b} + \frac{\delta_{inox}}{\lambda_{inox}} + \frac{1}{\alpha_1}}, W/m^2 \quad (9)$$

where t_n, t_m are water temperature and cooling brine temperature, ºC;

λ_b, λ_{ss} are thermal conductivity coefficient of the tape and the stainless steel wall, W/mK;

δ_x^{tb}, δ_{ss} are average ice layer thickness over time τand stainless steel wall thickness, m. The ice layer thickness changes over time, while the stainless-steel layer thickness is fixed $\delta = 3mm$.

α_1, α_2 are heat release coefficient from the stainless-steel wall into the salt water and from the water to the outer surface of the ice layer, W/m^2K.

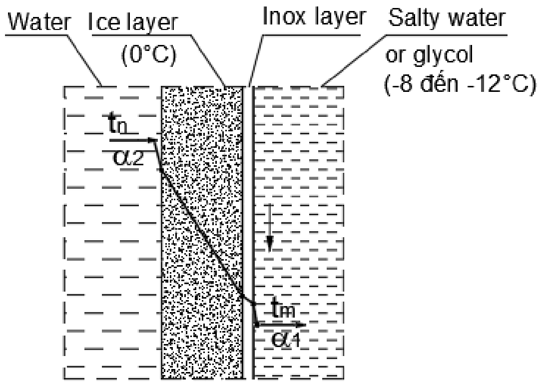

Fig. 3. Mathematical model of the freezing process on flat walls

The volume of ice adhered to 1 m² of wall surface during a period τ is defined as follows:

$$m_x = \rho_b.\delta_x, kg/m^2 \quad (10)$$

where δ_x is thickness of ice layer formed on a flat surface at time τ.

The amount of heat transferred to the saltwater through 1m ² of wall area after time τ is:

$$Q_\tau = m_x.q_r = \rho_b.\delta_x.q_r, J/m^2 \quad (11)$$

where q_r is the heat released by 1kg of water when petrified from temperature t_n to a certain temperature t_d and is calculated according to formula (4), J/kg.

The average heat flow from water to salt in time τ is determined as follows:

$$q = \frac{Q_\tau}{\tau} = \frac{\rho_b.\delta_x.q_r}{\tau}, W/m^2 \quad (12)$$

The relationship between time and ice thickness can be determined by balancing the heat transfer equation and the energy equation [1]:

$$q = \frac{t_n - t_m}{\frac{1}{\alpha_2} + \frac{\delta_x^{tb}}{\lambda_b} + \frac{\delta_{inox}}{\lambda_{inox}} + \frac{1}{\alpha_1}} = \frac{\rho_b.\delta_x.q_r}{\tau}, W/m^2 \quad (13)$$

Then the freezing time of the ice layer δx thickness is determined as follows [1]:

$$\tau = \frac{\rho_b.\delta_x.q_r}{t_n - t_m}\left[\frac{1}{\alpha_2} + \frac{\delta_x^{tb}}{\lambda_b} + \frac{\delta_{inox}}{\lambda_{inox}} + \frac{1}{\alpha_1}\right] \quad (14)$$

Replace $\delta_x^{tb} = \delta_x/2$ to equation (14), the final equation is defined as follows:

$$\tau = \frac{\rho_b.\delta_x.q_r}{t_n - t_m}\left[\frac{1}{\alpha_2} + \frac{\delta_x}{2\lambda_b} + \frac{\delta_{inox}}{\lambda_{inox}} + \frac{1}{\alpha_1}\right] \quad (15)$$

Equation (15) establishes the relationship between freezing time and the thickness of the ice layer formed on a flat surface. Fig. 4 shows this relationship with the thick stainless steel layer.

$\delta_{inox} = 3\text{mm},\ \lambda_{inox} = 16{,}3\text{W/mK},$

$\rho_b = 920\text{kg/m}^3, t_n = 0^o\text{C}, t_m = -12^o\text{C},$

$\lambda_b = \frac{2{,}236\text{W}}{\text{mK}}, \alpha_1 = \frac{2500\text{W}}{\text{m}^2\text{K}}, \alpha_2 = 2200\text{W/m}^2\text{K}.$

The results show that when freezing on a flat surface, the thickness of the ice layer formed is greater than that of the cylindrical surface at the same time. At the end of the process, the time to create the same thick layer of ice increases rapidly compared to the beginning stage.

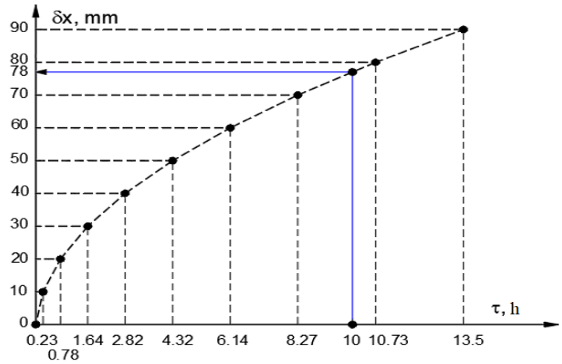

Fig. 4. Relationship δx= f(τ) of freezing process on flat surface

3. Defrosting Mathematical Model

3.1. Defrost the Ice on the Cylinder Surface

Fig. 5 shows the defrosting process model. Warm water or a cooling agent moves inside the tube and defrosts the ice on the outside of the tube. The thickness of the melting ice layer increases over time. In this study, the heat exchange process from the cold agent inside the tube to the inner surface of the ice layer is modeled with the assumption that the ice after melting is located between the tube and the ice layer is stationary and does not move [10].

The heat flow from warm water to the ice layer outside the pipe is defined as follows [9, 10]:

$$Q_L = \frac{t_m - t_{nd}}{\frac{1}{2\pi\lambda_n}ln\frac{d_x^{tb}}{d_2} + \frac{1}{2\pi\lambda_t}ln\frac{d_2}{d_1} + \frac{1}{\pi d_1\alpha_1}}, W/m \quad (16)$$

where

t_m, t_{nd} are average temperature of the cooling agent and outer layer temperature of just melted ice, ^oC;

λ_n , λ_t are thermal conductivity coefficient of water and pipe material, *W/mK*;

d_x^{tb}, d_2, d_1 are average outer diameter of the melt water layer during a time τ, outer and inner diameter of the refrigerant pipe, m;

α_1 is heat release coefficient towards the agent to be cooled, $W/m^2 K$.

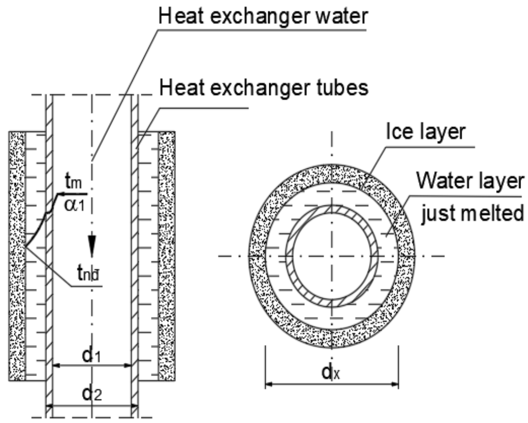

Fig. 5. Model of defrosting problem on pipe surface

The volume of ice melted per 1m of pipeline length after time τ is calculated as follows:

$$m_x = \pi\rho_b(r_x^2 - r_2^2), kg/m \quad (17)$$

where r_x, d_x are radius and diameter of dissolved water layer after time τ, m.

The heat of ice received from the medium in 1m of pipe after time τ is determined as follows:

$$Q_\tau = m_x.q_r = \pi\rho_b(r_x^2 - r_2^2).q_r, J/m \quad (18)$$

Then the average power during time τ is defined as follows:

$$Q_L = \frac{m_x.q_r}{\tau} = \frac{\pi\rho_b(r_x^2 - r_2^2).q_r}{\tau}, W/m \quad (19)$$

Balancing equations (16) and (19), the power is calculated as follows:

$$Q_L = \frac{t_m - t_{nd}}{\frac{1}{2\pi\lambda_n}ln\frac{d_x^{tb}}{d_2} + \frac{1}{2\pi\lambda_t}ln\frac{d_2}{d_1} + \frac{1}{\pi d_1\alpha_1}} = \frac{\pi\rho_b(r_x^2 - r_2^2).q_r}{\tau}, W/m \quad (20)$$

The relationship between time and thickness of ice layer melting [1] is defined as:

$$\tau = \frac{\pi\rho_b(r_x^2 - r_2^2).q_r}{t_m - t_{nd}}\left[\frac{1}{2\pi\lambda_n}ln\frac{d_x^{tb}}{d_2} + \frac{1}{2\pi\lambda_t}ln\frac{d_2}{d_1} + \frac{1}{\pi d_1\alpha_1}\right], s \quad (21)$$

Equation (21) then can be derrived as follows:

$$\tau = \frac{\rho_b (r_x^2 - r_2^2).q_r}{t_m - t_{nd}} \left[\frac{1}{2\lambda_n} ln \frac{d_x^{tb}}{d_2} + \frac{1}{2\lambda_t} ln \frac{d_2}{d_1} + \frac{1}{d_1 \alpha_1} \right], s \quad (22)$$

Replace

$r_x = r_2 + d_x$ and $d_x^{tb} = d_2 + 2\delta_x^{tb} = d_2 + \delta_x$

using the above formula, the relationship between

$\delta_x = f(\tau)$ is defined as follows [1]:

$$\tau = \frac{\rho_b [(r_2 + \delta_x)^2 - r_2^2].q_r}{t_m - t_{nd}} \left[\frac{1}{2\lambda_n} ln \frac{d_2 + \delta_x}{d_2} + \frac{1}{2\lambda_t} ln \frac{d_2}{d_1} + \frac{1}{d_1 \alpha_1} \right], s \quad (23)$$

Equation (23) shows an explicit relationship between time and the thickness of the ice layer formed. The calculation results are shown in Fig. 6.

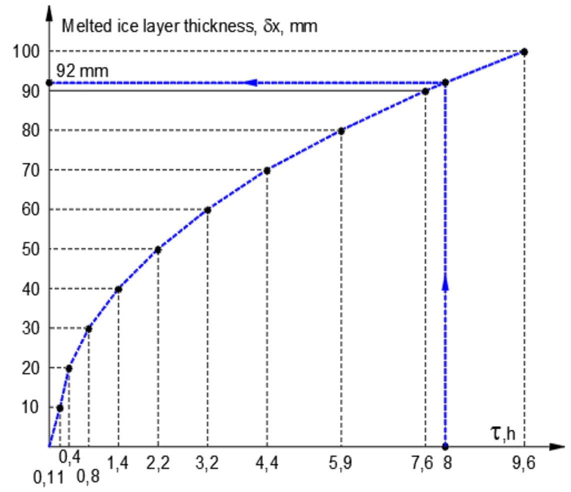

Fig. 6. Relationship $\delta_x = f(\tau)$ of defrosting process on pipes

The model is calculated with specific structural and thermophysical parameters of the medium as follows:

$t_m = 10^oC$, $t_{nd} = 0^oC$, $\rho_b = 920 kg/m^3$,

DN25 steel pipe (ϕ33.4/28, eighty-six),

$\lambda_n = 10 W/mK$, $\lambda_t = 45,6 W/mK$,

$\alpha_1 = 2500 W/m^2K$, $q_r = 333550 J/kg$.

The results are similar to the water-freezing process on the cylindrical surface. Compared to the freezing time, the defrosting time takes place faster under the same conditions and the same ice layer thickness. This is because the water's thermal resistance is smaller than the ice layer formed. Toward the end of the process, defrosting time becomes slower considering the same thickness of the defrosted ice layer.

3.2. Defrost on a Flat Surface

Fig. 7 shows the defrosting process on a flat surface. The agent to be cooled (warm water at 10 °C or glycol of equivalent temperature) moves across the flat surface and exchanges heat with the layer of ice adhering to the surface. The ice layer will gradually melt over time and it is necessary to determine the thickness of the melted ice layer over time τ. Consider the layer of melted water between the solid surface and the unmelted ice layer to be at rest.

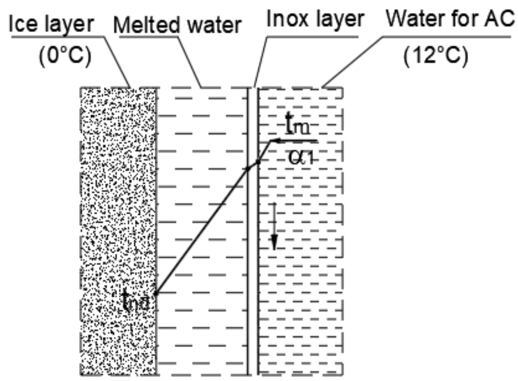

Fig. 7: Model of defrosting process on flat surface

The heat flow from the agent to be cooled through 1m² of flat wall area into ice water is determined according to the formula [9, 10]:

$$q = \frac{t_m - t_{nd}}{\frac{\delta_x^{tb}}{\lambda_n} + \frac{\delta_{Inox}}{\lambda_{Inox}} + \frac{1}{\alpha_1}}, W/m^2 \quad (23)$$

where λ_n, λ_{ss} are thermal conductivity coefficient of water and stainless steel wall, W/mK;

δ_x^{tb}, δ_{ss} are average thickness of melted ice layer over time τ and thickness of stainless steel layer, m.

The average thickness of the ice layer that melts over time τ is $\delta_x/2$.

α_1 is heat release coefficient from the agent to be cooled to the stainless steel wall surface, W/m²K.

The volume of ice adhered to 1 m² of wall surface during time τ is defined as follows:

$$m_x = \rho_b.\delta_x, kg/m^2 \quad (24)$$

where δ_x is thickness of melted ice layer after time τ, *m.*

The amount of heat received by the ice block from the agent that needs to be cooled through 1m² of wall area after time τ is defined as follows:

$$Q_\tau = m_x.q_r = \rho_b.\delta_x.q_r, J/m^2 \quad (25)$$

where q_r is the latent heat of freezing of water, *J/kg*.

The average heat flow transferred from the agent that needs to be cooled to the ice during the time τ is determined as follows:

$$q = \frac{Q_\tau}{\tau} = \frac{m_x.q_r}{\tau} = \frac{\rho_b.\delta_x.q_r}{\tau}, W/m^2 \quad (26)$$

Balancing (24) and (26), the average heat flow is determined as follows:

$$q = \frac{t_m - t_{nd}}{\frac{\delta_x^{tb}}{\lambda_n} + \frac{\delta_{Inox}}{\lambda_{Inox}} + \frac{1}{\alpha_1}} = \frac{\rho_b.\delta_x.q_r}{\tau}, W/m^2 \quad (27)$$

Then τ is calculated as follows

$$\tau = \frac{\rho_b.\delta_x.q_r}{t_m - t_{nd}}.\left[\frac{\delta_x^{tb}}{\lambda_n} + \frac{\delta_{Inox}}{\lambda_{Inox}} + \frac{1}{\alpha_1}\right], s \quad (28)$$

Replacing $\delta_x^{tb} = \delta_x/2$, equation (28) is defined as follows:

$$\tau = \frac{\rho_b.\delta_x.q_r}{t_m - t_{nd}}.\left[\frac{\delta_x}{2\lambda_n} + \frac{\delta_{Inox}}{\lambda_{Inox}} + \frac{1}{\alpha_1}\right], s \quad (29)$$

Equation (29) shows an explicit relationship between the thickness of the melted ice layer and the execution time. The calculation results are shown in Fig. 8. The model is calculated using a stainless steel wall thickness:

$\delta_{Inox} = 3mm, t_m = 10^oC, t_{nd} = 0^oC,$

$\lambda_n = 10W/mK, \lambda_{Inox} = 16{,}3W/mK,$

$\alpha_1 = 2500W/m^2K, q_r = 333550J/kg.$

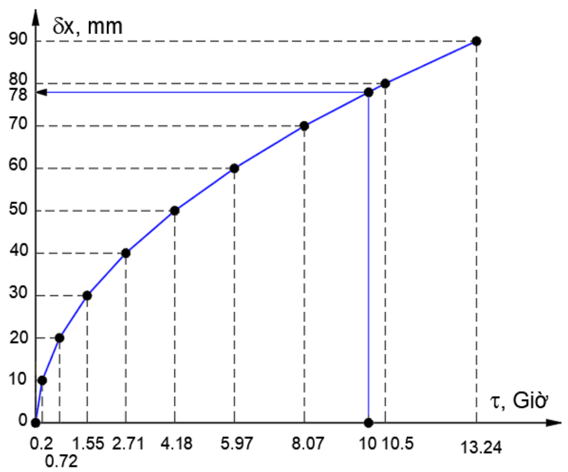

Fig. 8. Relationship between melting ice layer thickness and time, $\delta_x = f(\tau)$

The results show that the defrosting time takes place faster under the same conditions and the same ice layer thickness compared to the freezing time. This is because the thermal resistance of water is smaller than the thermal resistance of ice. Towards the end, defrosting time becomes slower considering the same thickness of defrosted ice layer.

4. Conclusion

In this study, the mathematical model of freezing and defrosting on cylindrical and flat surfaces is demonstrated. The results can be summarized as follows:

- Calculation results for specific cases show that, after a freezing time of about 10 hours, the thickness of the ice layer formed on cylindrical surfaces is about 55 mm, and on flat surfaces is about 80 mm, which shows that flat surfaces make better ice;

- Towards the end of the process, the thickness of the ice layer formed per unit of time decreases because the ice layer previously formed becomes an insulating layer that hinders the heat transfer process;

- The defrosting process is faster than the freezing process. If the convection movement inside the melted water layer is ta ken into account, the defrosting process is certainly faster.

The calculated data provide important parameters when arranging heat exchanger tubes and determining the actual freezing time to achieve the set technical requirements.

References

[1] Rahimi M, Afshari A, Fojan P, Gurevich L, The effect of surface modification on initial ice formation on aluminum surfaces, Applied Surface Science, vol. 355, pp. 327-333, Nov. 2015. https://doi.org/10.1016/j.apsusc.2015.06.201

[2] Yao X, Jin Z, Zhou Y, Yang Z, Impingement and freezing of two water droplets on an ice surface, International Journal of Multiphase Flow, vol. 169, Dec. 2023. https://doi.org/10.1016/j.ijmultiphaseflow.2023.104590

[3] Dongo P. D., Machrafi H, Minetti C., *et al*, A heat-pulse method for detecting i.ce formation on surfaces, Thermal Science Engineering Progress, vol. 22, May. 2021. https://doi.org/10.1016/j.tsep.2020.100813

[4] Mangini D., Antonini C., Marengo M., Amirfazli A., Runback ice formation mechanism on hydrophilic and superhydrophobic surfaces, Cold Regions Science and Technology, vol. 109, pp. 53-60, Jan. 2015. https://doi.org/10.1016/j.coldregions.2014.09.012

[5] Yin L., Xia Q., Xue J., *et al*, In situ investigation of ice formation on surfaces with representative wettability, Applied Surface Science, vol. 256, pp. 6764-6769, Sep. 2010. https://doi.org/10.1016/j.apsusc.2010.04.086

[6] M. Akyurt, G. Zaki, B. Habeebullah, Freezing phenomena in ice-water systems, Energy Conversion and Management, vol. 43, iss. 14, pp. 1773-1789, Sep. 2002. https://doi.org/10.1016/S0196-8904(01)00129-7

[7] Weihao Ling, Jingtao Wu, Xuan Li, Jianjun Ma, Yu Ding, Bingcheng Li, Min Zeng, Numerical prediction of frosting growth characteristics of microchannel louvered fin heat exchanger, Energy, vol. 283, Nov. 2023. https://doi.org/10.1016/j.energy.2023.128519

[8] Vo Chi Chinh, Research, design, manufacture and deploy application of heat storage equipment systems for medium and large capacity air conditioners to improve operating efficiency and avoid peak operating hours points in Da Nang city - City level project 2022.

[9] Dang Quoc Phu, Tran The Son, Tran Van Phu, Heat transfer, Education Publishing House, Hanoi 2003. (Vietnamese: Đặng Quốc Phú, Trần Thế Sơn, Trần Văn Phú - Truyền nhiệt - Nhà xuất bản Giáo dục, Hà Nội, 2003).

[10] Dinh Van Thuan, Vo Chi Chinh, Refrigeration systems and equipment, Science and Technology Publishing House, Hanoi, 2005. (Vietnamese: Đinh Văn Thuận, Võ Chí Chính- Hệ thống máy và thiết bị lạnh - Nhà xuất bản Khoa học kỹ thuật, Hà Nội, 2005).