

## Chapter SM 5 Thermal Storage Systems

### SM 5.1 Mechanisms of Freezing and Melting Ice

As discussed in Chapter 17, there are different ice making and ice storage configurations. However, they all involve the same phenomena of freezing water on a heat transfer surface during the charging period and melting the ice on a heat transfer surface during the discharge period. The basic heat transfer mechanisms are similar although the specific geometry of the systems may be different. In this chapter the freezing and melting of ice for geometries typical of ice storage systems are analyzed to provide insight into the performance of such systems.

A cross-section of a heat exchanger during ice-making is shown in Figure 5.1. A secondary fluid, which typically would be either a refrigerant or a water-glycol mixture, flows over a heat transfer surface. The temperature of the fluid is below the freezing point of water. On the other side of the surface is the water that will be the storage medium at a temperature above the freezing point. The water shown is stationary, although it could be flowing as in an ice harvester. As shown in Figure 5.1, a film of ice of thickness  $L$  forms on the heat exchanger surface next to the water. The temperature profile through the system is also shown. The temperature increases from that of the cold secondary fluid through the heat exchanger surface and ice layer to that of the water. At the ice–water interface where freezing occurs, the temperature equals the freezing temperature. The profile reflects the fact that thermal energy is released by freezing of the water and heat is transferred from the warm water through the ice layer to the secondary fluid.

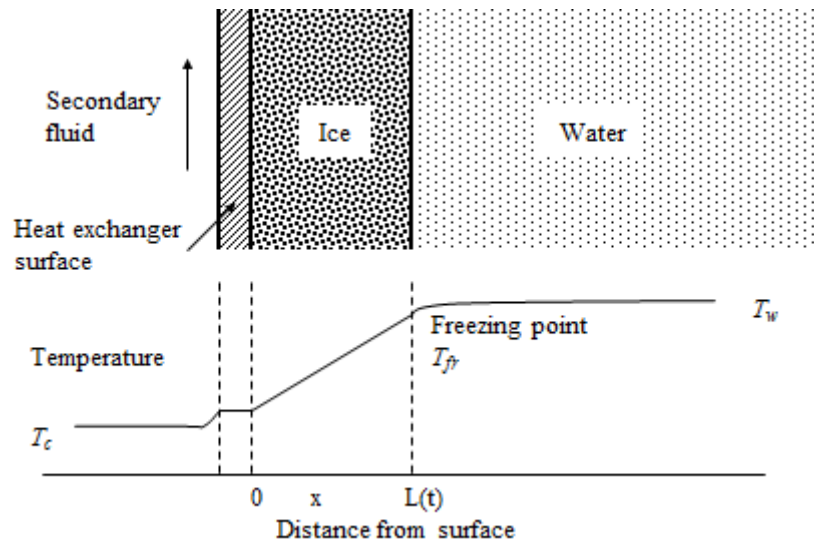


Figure 5.1 Schematic of ice making and temperature profile

This is a transient process in which the heat flow and temperatures vary with time. At the start of the freezing process, the only thermal resistances are those due to convection from the secondary fluid and to conduction in the heat exchanger surface. Thus, heat is readily transferred from the water through the heat exchanger surface to the fluid, and the water freezes rapidly. As the water freezes and the ice layer builds in thickness, the thermal resistance of the ice between the location where freezing occurs and the surface increases. The total resistance increases with time, causing the rate of heat transfer to decrease and the rate of growth of the ice layer to slow down.

A number of parameters affect the rates of freezing and melting of water, and a heat transfer analysis can be performed to establish the relation among them. The physical picture is shown on the left in Figure 5.2. The thickness of the ice layer at time  $t$  is  $L$ , and the interface between the ice and the water is at distance  $L$  from the cold surface. After a time increment  $\Delta t$  the interface is at a distance  $L + \Delta L$  from the cold surface. The system is a layer of water of fixed mass located initially at the distance  $L$  from the heat transfer surface, as shown on the right in Figure 5.2. During the freezing process the right side of the system boundary moves to the right because ice is less dense than water, and at the end of the time increment it is at the position  $L + \Delta L$ .

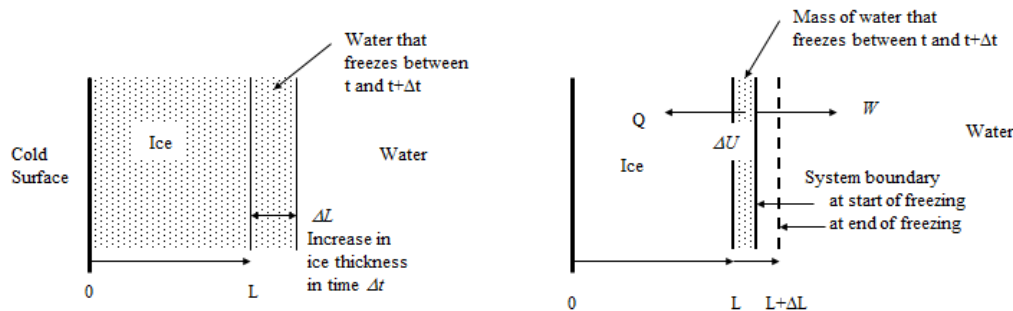


Figure 5.2 Schematic of the freezing of a water layer.

The relevant energy terms are also shown on the right of Figure 5.2. An amount of heat  $Q$  is transferred from the freezing water through the ice layer to the cold surface. Work is done on the water because the ice expands as it freezes and pushes the water away to the right. The internal energy of the system changes as the liquid water changes phase and becomes solid ice. The water layer is taken to be thin enough that over the small time increment the temperature is uniform and equal to the freezing temperature. It is also assumed that the temperature of the surrounding water is close to the freezing point so that there is negligible heat flow from the unfrozen water outside the control volume.

The heat and work energy flows are out of the system, and the energy balance for this process is

$$-Q - W = \Delta U \quad (5.1)$$

The heat flow can be written in terms of the heat flux, the area normal to the heat flow, and the time increment over which the process occurs, which is the time to freeze the layer:

$$Q = \dot{Q}'' A \Delta t \quad (5.2)$$

Work is done by the expansion of the system volume by amount  $\Delta V$ . The surrounding pressure is constant during the freezing process and the mass of the system is constant. Since the fluid in the system is liquid initially and solid at the end of the process, the change in volume can be expressed in terms of the system mass and the difference in specific volume between the liquid and the solid states:

$$W = p \Delta V = p \Delta(mv) = p m \Delta v = m p (v_i - v_f) \quad (5.3)$$

where  $m$  is the mass of the system,  $p$  is the pressure, and  $v_i$  and  $v_f$  are the specific volume of ice and liquid water, respectively.

The change in internal energy during the process is the difference in internal energy between the solid state and liquid states and can be written in terms of the mass and the specific internal energy as

$$\Delta U = U_{t+\Delta t} - U_t = m (u_i - u_f) \quad (5.4)$$

where  $u_i$  and  $u_f$  are the specific internal energy of ice and liquid water, respectively.

The mass of the system equals the density of ice times the final volume, which is expressed as the area and the distance the interface moves,  $\Delta L$ :

$$m = \rho_i A \Delta L \quad (5.5)$$

Combining these terms yields the heat transfer rate in terms of the properties and the change in thickness. Substituting equations 5.2, 5.3, 5.4, and 5.5 into 5.1 yields the energy balance for the process:

$$- \dot{Q}'' A \Delta t - \rho_i A \Delta L (p (v_i - v_f)) = \rho_f A \Delta L (u_i - u_f) \quad (5.6)$$

Because the pressure is constant, the internal energy and work terms can be combined into the enthalpy change during freezing, which is the latent heat of fusion  $h_{if}$ . The area can be canceled out and the energy balance can be rewritten as

$$\dot{Q}'' \Delta t = \rho_i \Delta L \left[ (u_f + p v_f) - (u_i + p v_i) \right] = \rho_i \Delta L h_{if} \quad (5.7)$$

Dividing the terms in equation 5.7 by the time increment  $\Delta t$  and passing to the limit of  $\Delta t$  approaching zero yields a differential equation that relates the heat flux from the ice to the rate of growth of the ice layer:

$$\dot{Q}'' = \rho_i h_{if} \frac{dL}{dt} \quad (5.8)$$

The heat flux can also be related to the difference in temperature between the ice-water interface and the secondary fluid. The thermal resistance between these locations is the sum of the convection resistance on the cold fluid side, the heat exchanger surface conduction resistance, and the conduction resistance through the ice layer. The thermal storage associated with cooling of the layer of ice below the freezing point and in the heat exchanger surface is assumed to be negligible, so that the heat flow through these elements can be treated using a steady-state relation.

It is convenient to add the convection resistance and the heat exchanger surface resistance together and then to use a conductance  $U$ , which is the reciprocal of the sum of these two resistances. The conduction resistance of the ice layer is its thickness, which is a function of time, divided by the thermal conductivity of ice. The heat flux can then be written in terms of the overall temperature difference and total thermal resistance as

$$\dot{Q}'' = \frac{(T_{fr} - T_c)}{\frac{1}{U} + \frac{L}{k_i}} \quad (5.9)$$

where  $T_{fr}$  is the temperature at which the ice is freezing (32 °F, 0 °C),  $T_c$  is the temperature of the cold circulating fluid, and  $k_i$  is the conductivity of ice. Using equation 5.9 to eliminate the heat flux from equation 5.8 yields a differential equation describing the rate of growth of the thickness of the ice layer,  $L$ , with time as

$$\frac{dL}{dt} = \frac{(T_{fr} - T_c)}{\rho_i h_{if} \left( \frac{1}{U} + \frac{L}{k_i} \right)} \quad (5.10)$$

Equation 5.10 can be integrated analytically for the situation of a constant secondary fluid temperature  $T_c$ . The thickness  $L$  appears in the denominator on the right-hand side of the equation, and so the variables must be separated in order to perform integration.

Integrating from the start of freezing when the thickness  $L$  is zero to time  $t$  when the thickness is  $L$  and then rearranging the result yield the following expression for the ice thickness as a function of time:

$$L = \sqrt{\frac{2(T_{fr} - T_c) k_i t}{\rho_i h_{if}}} + \left(\frac{k_i}{U}\right)^2 - \left(\frac{k_i}{U}\right) \quad (5.11)$$

Equation 5.11 shows that the thickness of the ice layer basically increases as the square root of time. There is initially a rapid increase in thickness, and then the rate of growth slows down. The thickness at any time is greater when the conductance between the coolant and the inside surface of the evaporator is larger. The design parameters that can be altered in an ice storage system are the coolant temperature and conductance. All of the other parameters are properties of either ice or water.

The limit of an infinitely large conductance  $U$  corresponds to a negligible resistance for the sum of the coolant convection and the heat exchanger surface resistances. For this situation, the term  $(k_i/U)$  is negligible. The thickness as a function of time is then given by

$$L_{\max} = \sqrt{\frac{2(T_{fr} - T_c) k_i t}{\rho_i h_{if}}} \quad (5.12)$$

Equation 5.12 yields the maximum rate at which ice can form and thus provides a limit on the maximum possible charging rate.

The water and ice properties are summarized in Table 5.1.

Table 5.1 Properties of water and ice

|                       | English units           | SI units                 |
|-----------------------|-------------------------|--------------------------|
| Freezing temperature  | 32 °F                   | 0 °C                     |
| Density: water:       | 62.4 lb/ft <sup>3</sup> | 1000 kg/m <sup>3</sup>   |
| ice                   | 57.0 lb/ft <sup>3</sup> | 913 kg/m <sup>3</sup>    |
| Conductivity: water   | 0.6 Btu/hr-ft-°F        | 3.4 W/m <sup>2</sup> -°C |
| ice                   | 1.2 Btu/hr-ft-°F        | 6.8 W/m <sup>2</sup> -°C |
| Latent heat of fusion | 144 Btu/lb              | 335 kJ/kg                |

Equations such as 5.11 and 5.12 that predict the growth of ice on surfaces are important in the design of ice storage systems and analysis of their performance. Example 5.1 illustrates the calculation of the thickness of an ice layer.

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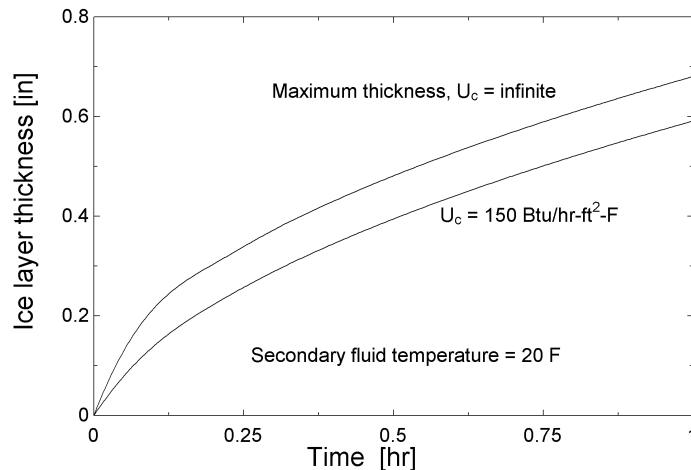
Example 5.1 Determine the maximum thickness of an ice layer after one hour of charging for a system with a secondary fluid temperature of 20 °F. Determine also the thickness for an overall conductance of 150 Btu/hr-ft<sup>2</sup>-°F.

The limit for the maximum possible thickness will be given for the case of a very large conductance by equation 5.12. Using the properties given in Table 5.1, after one hour, the thickness of the ice layer is

$$L_{\max} = \sqrt{\frac{2 * (32 - 20) (F) * 1.2 (Btu / hr - ft - F) * 1 (hr)}{57 (lbm / ft^3) * 144 (Btu / lbm)}} = 0.057 ft = 0.68 in.$$

This example shows that it takes considerable time to build up an ice layer of appreciable thickness. The only way to build a thicker layer in this time period would be to decrease the temperature of the secondary fluid. If the fluid temperature were dropped to 8 °F, which would double the temperature difference, the maximum thickness would increase to only 1 inch after one hour of charging.

The thickness of the ice layer as a function of time is shown in the figure below for a negligible resistance for the convection and heat transfer surface, corresponding to an infinite conductance, and a secondary fluid temperature of 20 °F.



Also shown is the thickness calculated from equation 5.11 for a conductance of 150 Btu-hr-ft<sup>2</sup>-°F, which is representative of a commercial icemaker. The thermal resistance due to the combination of the coolant convection coefficient and the heat exchanger surface reduces the rate at which ice forms significantly and needs to be taken into account in the design of ice storage systems.

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The situation for the melting of an ice layer during discharge is similar to that during freezing. The temperature of the secondary fluid is now higher than the freezing point, and during the melting process a layer of water, rather than ice, forms next to the heat

transfer surface. Heat is transferred through this water layer to the ice. It is assumed that there is no convection in the thin layer of water between the heat transfer surface and the water-ice interface. Then, in equation 5.9 the thermal resistance of the ice layer is replaced with that for water:

$$\dot{Q}'' = \frac{(T_c - T_{fr})}{\frac{1}{U} + \frac{L}{k_f}} \quad (5.13)$$

where  $T_c$  is the temperature of the secondary fluid, which is now higher than the freezing temperature. The analysis for the rate of melting is the same as that for freezing, but with the appropriate properties. The thickness of the water layer at any time of discharge is given by equation 5.11, with the conductivity of ice replaced by that for water since the heat is conducted through the water layer and the density of ice replaced by that for water since the volume is water that has melted:

$$L = \sqrt{\frac{2(T_c - T_{fr})k_f t}{\rho_f h_{if}}} + \left(\frac{k_f}{U}\right)^2 - \left(\frac{k_f}{U}\right) \quad (5.14)$$

The limit on the maximum rate of discharge is again given by the situation when the conductance is very large. For this condition, equation 5.14 becomes

$$L_{\max} = \sqrt{\frac{2(T_c - T_{fr})k_f t}{\rho_f h_{if}}} \quad (5.15)$$

During discharge, the heat flow rate is more important than the thickness of the water layer since this is the cooling that is supplied to the building. An expression for the maximum possible rate of heat transfer during discharge is obtained by substituting equation 5.15 into equation 5.13, with the term  $L/U$  negligible to  $L/k_f$ :

$$\dot{Q}_{\max}'' = \sqrt{\frac{(T_c - T_{fr})\rho_f h_{if} k_f}{2t}} \quad (5.16)$$

As with charging, the heat flux is initially very high but then decreases rapidly as the water layer increases in thickness. The heat flux is proportional to the reciprocal of the square root of time. Because the thermal conductivity of water is about one-half that of ice, the rate of discharge is slower than that for charging and the heat transfer rate is less for the same temperature difference. The secondary fluid temperature can be raised

somewhat to increase the rate of heat transfer, but the temperature is limited by the application. For building air conditioning, the highest temperature of the secondary fluid occurs when it leaves the cooling coil, which is in the range of 50 to 60 °F. This represents the maximum temperature for the fluid entering the ice store, and the maximum temperature difference is about 25 °F. Example 5.2 illustrates the calculation of the rate of discharge from melting ice.

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**Example 5.2** Determine the maximum possible heat flux and the corresponding thickness of the water layer after one hour of melting of an ice layer. The secondary fluid enters at 60 °F.

The maximum thickness of the water layer after one hour of discharge is given by equation 5.15:

$$L_{\max} = \sqrt{\frac{2*(60-32)(F)*0.6(Btu/hr-ft-F)*1(hr)}{62.4(lbm/ft^3)*144(Btu/lbm)}} * 12(in/ft) = 0.74 inch$$

The thickness of the water layer after one hour of melting is slightly greater than that of the ice layer that is built up in one hour (example 5.1). Even though the conductivity of water is less than that of ice, the temperature difference between the fluid and freezing is larger.

The maximum heat flux from the melting ice layer is given by equation 5.16. After one hour the maximum heat flux is

$$\dot{Q}_{\max}'' = \sqrt{\frac{(60-32)(F)*62.4(lbm/ft^3)144(Btu/lbm)*0.6(Btu/hr-ft-F)}{2*1(hr)}} = 275 Btu/hr-ft^2$$

This is not a very large heat flux. To put this value of heat flux into perspective, the amount of surface area required to meet a representative building cooling load of 100 tons will be estimated. The ice surface area to yield this amount of cooling after the ice storage system has been operating for one hour is the total heat transfer rate divided by the heat flux:

$$Area = \frac{\dot{Q}}{\dot{Q}''} = \frac{100(tons)*12,000(Btu/ton-hr)}{275(Btu/hr-ft^2)} = 4,364 ft^2$$

The heat exchange surface areas exposed to the ice must be very large to meet the cooling loads with an ice storage system. Storage tanks are often made as coils of tubes



immersed in tanks filled with water. For a tank with one-half inch diameter tubes, the length to provide this heat transfer area is about 35,000 feet, or about seven miles.

Another perspective is given by the total amount of ice that would be needed to provide cooling. The total volume of ice needed to meet the cooling load of a building with an average load of 100 tons over a 10-hour day would be

$$V = \frac{Q}{\rho h_{if}} = \frac{1000(\text{ton} - \text{hr}) * 12,000(\text{Btu} / \text{ton} - \text{hr})}{57(\text{lb} / \text{ft}^3) * 144(\text{Btu} / \text{lb})} = 1,462 \text{ ft}^3$$

This volume corresponds to a cube of ice that is about 12 feet on a side. Although the volume of ice storage is not excessive, the heat transfer rates from the ice are low and large heat transfer areas are needed.

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Examples 5.1 and 5.2 show that the heat transfer rates during the charging and discharging of an ice storage tank need to be considered during design. A thick ice layer may have a significant cooling capacity, but the resistance of the water layer formed during melting seriously limits the rate of discharge. The volume of ice must be distributed in thin layers over a large area so that the rate of heat transfer is high enough to meet the instantaneous load and the ice is effectively employed.

A common method of constructing a storage tank is to wind plastic tubes in a coil and place them in a tank that is then filled with water. A cross-section of this geometry during discharge is shown in Figure 5.3. The tubes are placed close together so that the thickness of ice on the outside of the tubes will be thin. This is the internal melt ice-on-coil arrangement for a storage tank and allows the thin layers and large area necessary to obtain high rates of charging and discharging.

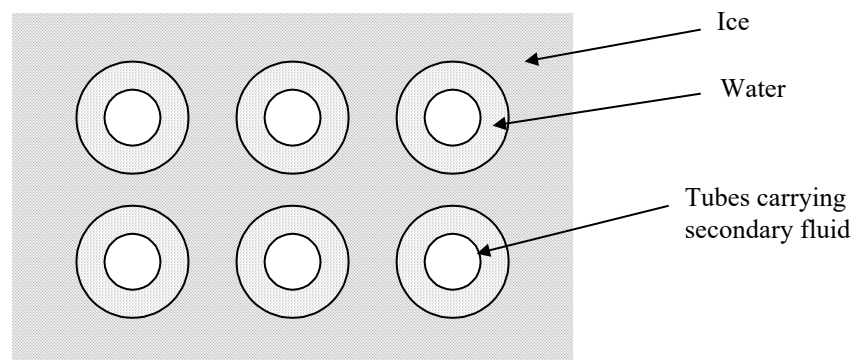


Figure 5.3 Cross section of tubes in the tank of an ice storage tank

The buildup of ice around a tube is similar to that on a plane wall, with the difference that as the ice builds up the thermal resistance between the ice–water interface and the inside of the tube is a function of the radius as well as thickness and increases more

rapidly than for the plane wall. The heat flow from the interface due to freezing is given by equation 5.8. It is more convenient to use the heat flow per unit tube length  $\dot{Q}'$  than the heat flux, and equation 5.8 becomes

$$\dot{Q}' = 2\pi r \rho_i h_{if} \frac{dr}{dt} \quad (5.17)$$

where  $r$  is the radial distance from the center of the tube to the interface.

As with the plane wall, the heat flux can be related to the difference in temperature between the ice–water interface and the secondary fluid. The coolant convection resistance and the heat exchanger surface resistance are represented by a conductance  $U$ . The conductance thermal resistance of the ice layer is given by

$$R_{ice} = \frac{\ln(r/r_o)}{2\pi k_i} \quad (5.18)$$

where  $r_o$  is the outer radius of the tube wall where the ice layer initiates and  $r$  is a function of time. Thermal storage in the ice layer and tube wall is assumed to be negligible so that the heat flow through these elements can be treated as a steady state flow. The heat flow can then be written in terms of the overall temperature difference and total thermal resistance similar to equation 5.9 as

$$\dot{Q}' = \frac{(T_{fr} - T_c)}{\left( \frac{1}{2\pi r_o U} + \frac{\ln(r/r_o)}{2\pi k_i} \right)} \quad (5.19)$$

Equating the heat flow expressions equation 5.17 and 5.19 to eliminate the heat flow yields a differential equation describing the rate of growth of the radial distance of the ice layer,  $r$ , with time as

$$\frac{dr}{dt} = \frac{(T_{fr} - T_c) \left( \frac{k_i}{\rho_i h_{if}} \right)}{\left( \frac{k_i}{r_o U} + \ln(r/r_o) \right) r} \quad (5.20)$$

It is not possible to integrate equation 5.20 analytically as for a plane wall. Equation 5.20 can be integrated numerically and the thickness of the ice layer on a circular tube is shown in Figure 5.4 in comparison to the thickness for a plane ice layer on a wall. The

maximum thickness of the layer as a function of time, which occurs when the conductance is very large, is shown on the left, and the thickness when there is a conductance of  $150 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$  is shown on the right. The two tube diameters, 0.5 in and 1.0 in, are representative of commercial ice makers. The thickness of ice on a circular tube is 20 to 30% less than that on a plane wall for the same conditions.

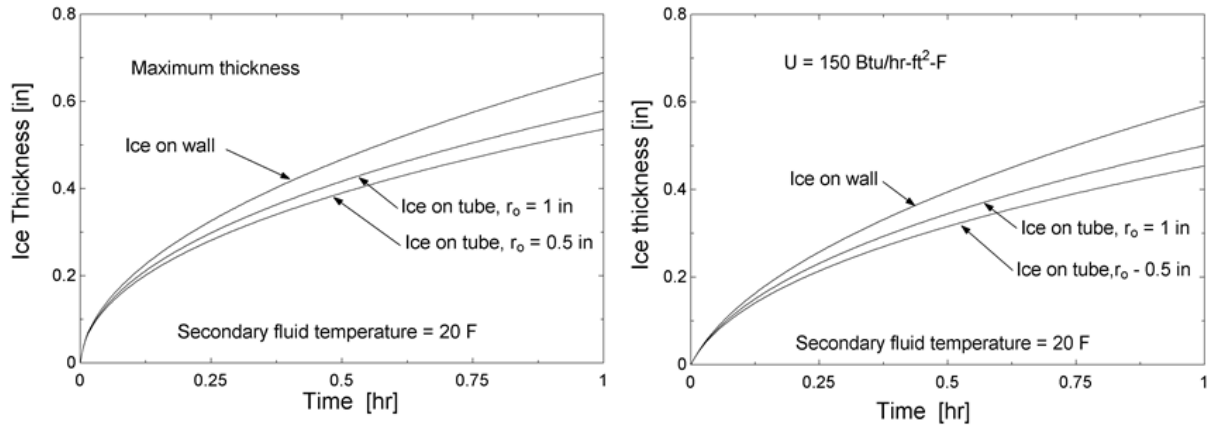


Figure 5.4 Ice thickness on circular tubes

As the ice layers grow on the tubes, the edges of the layers will eventually meet, leaving a small volume of water trapped between the ice layers as shown in Figure 5.5. This residual water volume is difficult to freeze in that its surface area continually diminishes and the thermal resistance increases as freezing progresses.

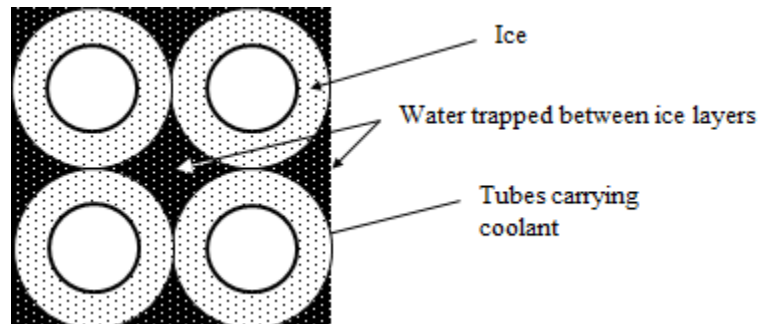


Figure 5.5 Ice layer buildup on circular tubes

There are two impacts of the interference of the circular tube ice layers on the requirements of an ice storage system. The first is that all of the water cannot be readily frozen, and thus the storage must be physically large enough to accommodate the unfrozen water. Then, during discharge, as water forms around the tubes the water between the tubes may cause ice to float to the top of the tank where it is slower to melt, further reducing the rate of discharge. The second effect is that the ice-making period is limited by the geometry. For example, for 1 inch tubes spaced on 2 inch centers, the

thickness of the ice layers is limited to about 0.5 inches on each tube. As shown in Figure 5.11, charging and discharging periods are on the order of one to two hours.

### ***SM 5.2 Summary***

The heat exchanger effectiveness concept is useful in describing the performance of storage media. The effectiveness is primarily a function of the amount of cooling that has been provided from the tank, with a secondary dependency on the flow rate through the tank. The mechanisms involved in the freezing and thawing of water govern the effectiveness. Ice that is built up on the heat transfer surfaces presents an increasing thermal resistance to heat transfer over time, and ice layers need to be thin to allow charging of the store in a reasonable amount of time.

Correspondingly, the melting of ice produces layers of water with low thermal conductivity, and these layers need to be thin to allow a high rate of discharge. These mechanisms lead to a heat transfer rate limits for ice storage systems.

### ***SM 5.3 Nomenclature***

|             |                                          |                   |                                              |
|-------------|------------------------------------------|-------------------|----------------------------------------------|
| $A$         | area                                     | $U$               | internal thermal energy, overall conductance |
| $h_{if}$    | latent heat of fusion                    | $v$               | specific volume                              |
| $k$         | thermal conductivity                     | $V$               | total volume                                 |
| $L$         | thickness of ice layer                   |                   |                                              |
| $m$         | mass                                     |                   |                                              |
| $\dot{Q}$   | heat flow                                | $\Delta$          | difference                                   |
| $\dot{Q}$   | heat flow rate                           | $\rho$            | density                                      |
| $\dot{Q}'$  | heat flow rate per unit length           |                   |                                              |
| $\dot{Q}''$ | heat flux (heat flow rate per unit area) |                   |                                              |
| $p$         | pressure                                 | <u>Subscripts</u> |                                              |
| $r$         | radius                                   | c                 | coolant                                      |
| $r_o$       | tube radius                              | f                 | liquid phase                                 |
| $R$         | thermal resistance                       | fr                | freezing                                     |
| $t$         | time                                     | i                 | ice phase                                    |
| $T$         | temperature                              | ice               | ice layer                                    |
| $W$         | work transfer                            | max               | maximum rate                                 |
| $u$         | specific internal thermal energy         | w                 | water phase                                  |

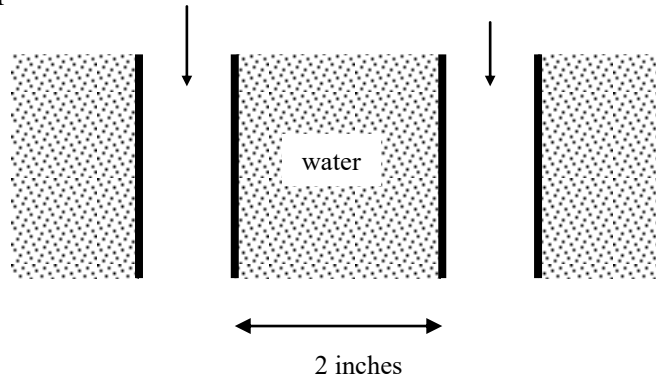
### ***SM 5.4 References***

- ASHRAE, 2007 *ASHRAE Handbook—HVAC Applications*, Chapter 34, Thermal Storage, ASHRAE, Atlanta, 2007
- Jekel, T. B., J. W. Mitchell, and S. A. Klein, "Modeling of Ice-Storage Tanks," *ASHRAE Trans.* 99, 1 (1993)

## Problems

### Problems in English Units

- 5.1 An ice storage unit consists of alternating parallel passages of a glycol circulating fluid and water/ice as shown below. The channels are made of thin steel plates and the circulating fluid heat transfer coefficient is  $200 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ . The temperature of the circulating fluid is  $18^\circ\text{F}$  during charging and  $50^\circ\text{F}$  during discharge, and the circulating fluid flow rate is high enough that the ice and water layers are constant in the flow direction. Assume that the water is fully mixed as it cools above the freezing temperature.

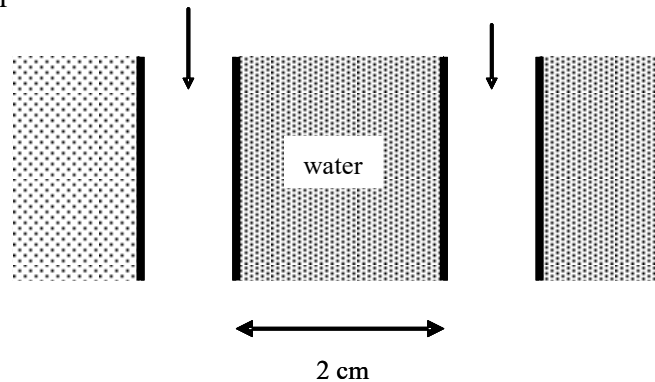


- Estimate the time it takes to fully charge the system (freeze the ice completely) after the storage is fully discharged.
  - Determine and plot the cooling rate during discharge as a function of time.
  - Draw some conclusions from your analysis.
- 5.2 For the ice storage unit of Problem 5.1, the channels are 0.2 inches wide and 10 feet long. The circulating fluid is ethylene glycol and it enters the storage at  $50^\circ\text{F}$ . The heat flux can be calculated using the average temperature of the circulating fluid. The properties of ethylene glycol are density =  $70 \text{ lbm/ft}^3$ , specific heat =  $0.75 \text{ Btu/lbm-F}$ , thermal conductivity =  $0.2 \text{ Btu/hr-ft-F}$ , and viscosity =  $60 \text{ lbm/hr-ft}$ .
- Determine and plot the fluid outlet temperature during discharge as a function of time for velocities of 0.1, 0.2, and 0.3 ft/s.
  - The cooling is useful when the outlet temperature is  $45^\circ\text{F}$  or less. Estimate the time that the storage provides useful cooling and the amount of cooling provided.
  - Draw some conclusions from your analysis.

### Problems in SI Units

- 5.3 An ice storage unit consists of alternating parallel passages of a glycol circulating fluid and water/ice as shown below. The channels are made of thin steel plates and the circulating fluid heat transfer coefficient is  $1000 \text{ W/m}^2\text{-}^\circ\text{C}$ . The temperature of

the circulating fluid is  $-8\text{ }^{\circ}\text{C}$  during charging and  $10\text{ }^{\circ}\text{C}$  during discharge, and the circulating fluid flow rate is high enough that the ice and water layers are constant in the flow direction. Assume that the water is fully mixed as it cools above the freezing temperature.



- a. Estimate the time it takes to fully charge the system (freeze the ice completely) after the storage is fully discharged.
  - b. Determine and plot the cooling rate during discharge as a function of time.
  - c. Draw some conclusions from your analysis.
- 5.4 For the ice storage unit of Problem 5.3, the channels are 5 mm wide and 3 m long. The circulating fluid is ethylene glycol and it enters the storage at  $15\text{ }^{\circ}\text{C}$ . The heat flux can be calculated using the average temperature of the circulating fluid. The properties of ethylene glycol are density =  $1120\text{ kg/m}^3$ , specific heat =  $3.1\text{ kJ/kg}\cdot\text{C}$ , thermal conductivity =  $0.35\text{ W/m}\cdot\text{C}$ , and viscosity =  $0.025\text{ kg/m}\cdot\text{s}$ .
- a. Determine and plot the fluid outlet temperature during discharge as a function of time for velocities of 0.03, 0.06, and 0.1 m/s.
  - b. The cooling is useful when the outlet temperature is  $7\text{ }^{\circ}\text{C}$  or less. Estimate the time that the storage provides useful cooling and the amount of cooling provided.
  - c. Draw some conclusions from your analysis.

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