Isı Bilimi ve Tekniği Dergisi, 29, 2, 75-87, 2009
J. of Thermal Science and Technology

ISSN 1300-3615

# ICE FORMATION AROUND A HORIZONTAL TUBE IN A RECTANGULAR VESSEL

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(Geliş Tarihi : 24.12.2008, Kabul Tarihi : 25.05.2009)

**Abstract:** This paper investigates phase change phenomena around a horizontal tube during a cooling process of thermal storage. Experiments are performed to investigate the effects of different heat transfer fluid inlet temperatures on ice formation around the tube. Supercooling temperature and the time for the start of nucleation of water are observed by measuring the time variations of temperature profiles at various locations inside the test vessel. The thickness of the ice formed around the tube was measured at different axial positions along the tube during the experiments. A mathematical model to predict ice formation around the tube is proposed. Comparison of the results of the model with that of the experiments showed that the agreement between the two is acceptable, although the model is simple.
**Keywords:** Ice storage, Nucleation, Phase change, Supercooling.

# DİKDÖRTGEN BİR TANK İÇERİSİNDE YATAY BİR BORU ETRAFINDAKİ BUZ OLUŞUMU

**Özet**: Bu çalışmada soğu enerjisi depolamasında kullanılan yatay bir boru etrafındaki faz değişimi araştırılmıştır. Farklı ısı transfer akışkanı sıcaklıklarının buz oluşumuna etkisini incelemek için deneyler yapılmıştır. Test tankı içerisinde farklı noktalarda sıcaklıkların ölçülmesiyle, suyun aşırı soğuma sıcaklığı ve zamanı tespit edilmiştir. Deney süresince boru etrafındaki buz kalınlığı farklı eksenel pozisyonlarda ölçülmüş ve boru etrafındaki buz oluşumunu tespit edebilmek için bir matematik model oluşturulmuştur. Model basit bir model olmasına rağmen, deneysel sonuçlarla model sonuçlarının birbiri ile uyumlu olduğu görülmüştür.
**Anahtar Kelimeler**: Buz depolama, Çekirdekleşme, Faz değişimi, Aşırı soğuma

## NOMENCLATURE

| | |
|---|---|
| $h_{ew}$ | latent heat [kJ/kg] |
| $h_a$ | heat transfer coefficient between ambient and outer surface of the vessel [$Wm^{-2}K^{-1}$] |
| $h_{ci}$ | heat transfer coefficient between water and inner surface of the vessel [$Wm^{-2}K^{-1}$] |
| $h_i$ | heat transfer coefficient inside tube [$Wm^{-2}K^{-1}$] |
| $k_e$ | thermal conductivity of ice [$Wm^{-1}K^{-1}$] |
| $k_i$ | thermal conductivity of the insulation ice [$Wm^{-1}K^{-1}$] |
| $k_p$ | thermal conductivity of the plexiglas [$Wm^{-1}K^{-1}$] |
| $k_w$ | thermal conductivity of tube material [$Wm^{-1}K^{-1}$] |
| L | tube length [m] |
| $P_a$ | outer peripheries of the vessel [m] |
| $P_{em}$ | periphery of ice [m] |
| $P_i$ | periphery [m] |
| $P_{ic}$ | the inner peripheries of the [m] |
| $P_{mi}$ | mean periphery of the insulating material [m] |
| $P_{mp}$ | mean periphery of the plexiglas [m] |
| $P_{wm}$ | periphery of tube [m] |
| $\dot{Q}_g$ | heat gain [W/m] |
| $\dot{Q}_x$ | heat transfer rate [W/m] |
| r | radial coordinate thermal conductivity of tube material |
| $R_a$ | thermal resistance between ambient and ice-water surface |
| $R_i$ | inner radius of tube [m] |
| $R_o$ | outer radius of tube [m] |
| $R_p$ | thermal resistance for periphery |
| $R_p^*$ | dimensionless thermal resistance for periphery |
| $R_{po}$ | thermal resistance for inner side of the tube and pipe wall |
| $s_e$ | thickness of ice [m] |
| $s_e^*$ | dimensionless ice thickness |
| $s_i$ | thickness of the insulation [m] |
| $s_p$ | thickness of the plexiglas [m] |
| $s_w$ | thickness of tube wall [m] |
| t | time [s] |
| t* | dimensionless time |
| $T_e$ | ice-water temperature [ºC] |
| $T_f$ | temperature of heat transfer fluid [ºC] |
| x | axial coordinate |
| $\rho_e$ | density of ice [$kg/m^3$] |

## INTRODUCTION

Cool thermal energy storage is a technology that shifts electricity demand from on-peak period to off-peak hours, reducing peak demand. It also reduces electricity bills due to use of electricity for cooling during the periods when electricity prices are lower (Hasnain, 1998). These systems utilize a storage medium to store cooling produced during off-peak hours. The stored energy is later used during peak hours to meet an air-conditioning or process-cooling load. Various media such as chilled water, ice, or phase-change-materials can be used to store energy (Dorgan and Elleson, 1993).

Ice cool thermal energy storage systems are often classified as static or dynamic, according to the way ice is delivered to the storage tank. In dynamic systems, ice is produced outside the storage tank and removed from the ice-making surface continuously (Dincer, 2002). In static systems, an ice-making pipe is installed in the storage tank where ice is formed and later melted. Ice-on-coil systems produce ice outside a coil. The ice may be melted using either an external melting system, which melts ice from the outer side, or an internal melting system (Dincer, 2002).

Understanding of the solid-liquid phase change heat transfer phenomena around cylindrical tubes is needed for design of efficient ice-on-coil cool thermal energy storage systems. Sasaguchi et al. (1997) studied the solidification around a single and two vertically space cylinders in a fixed volume. In their study, pure water was used as the working fluid and the non-Boussinesq model was utilized to simulate the buoyancy driven flow. Sasaguchi et al. (1997) investigated effect of the initial water temperature on the transient cooling of water around a cylinder in a rectangular enclosure. Inteman and Kazmierczak (1997) studied heat transfer and ice formations deposited upon staggered and an in-line tube bank configuration. The first part of the study focuses on the global aspects of the phase change phenomenon and the second part of the study continues the analysis by investigating the convection phenomenon close-up. A review of researches on a variety of water freezing and ice melting problems was given by Fukusako and Yamada (1993). Habeebullah (2007) investigated growth rate of ice on the outside of cooled copper tubes. Ice formation around an isothermally cooled horizontal cylinder and effect of natural convection were studied by Cheng et al. (1988). A similar work on ice formation and heat transfer with water flow around cooled cylinders was reported by Hirata and Matsui (1990). Stampa and Nieckle (2005) studied numerically the growth of an ice layer formed outside a vertical tube, inside an annular cavity. Ismail et al. (2000) presented a numerical model for the solidification of phase change material around a radially finned tube with a constant inner wall temperature. In their study, numerical experiments were performed to investigate the effects of the number of fins, fin thickness, fin material, aspect ratio of tube arrangement and tube wall temperature. Erek et al. (2005) studied numerically and experimentally the solidification around the horizontal radially finned tube by considering fully developed velocity profile in the tube. Effect on cold thermal energy storage of heat transfer fluid inlet temperature, flow rate, fin density and fin size were investigated by Kayansayan and Acar (2006). They experimentally tested a total of seven tube configurations including a bare tube. Milon and Braga (2003) developed an experimental apparatus to investigate the supercooling phenomenon of water inside cylindrical capsules used for cool thermal energy storage process. They investigated supercooling period of the water and the nucleation temperature for different heat transfer fluid temperatures. Sparrow and Broadbent (1983) investigated freezing of an initially superheated or nonsuperheated liquid in a cooled vertical tube. Measurements were made which yielded information about the freezing front and the frozen mass, about the various energy components extracted from the tube. Sparrow and Bahrami (1980) performed experiments to determine the natural convection heat flux distribution on the faces of isothermal circumferential fins affixed to a horizontal cooled tube. Sparrow and Hsu (1981) solved the conjugate phase change convection problem which results when a coolant passes through a tube situated in a liquid phase-change medium. It was reported that, there is generally axial variation of the solid thickness along the tube because of the increase in the coolant temperature as it warms up along the length.

Although thermal energy storage systems for cooling were first used commercially in the 1940s and have gaining popularity in the USA and Europe in recent years, application of these systems are very limited in Turkey. Although there has been an interest in these systems in recent years, barriers still exist in Turkey regarding the application of these systems; such systems are not well known, they are relatively expensive because storage tanks are imported and they are notorious for troublemaking.

Büyükalaca et al. (2003) designed and constructed an ice-on-coil type ice storage tank and air-conditioned two rooms located inside the Laboratories of Mechanical Engineering Department of Çukurova University, Adana, Turkey. General view of the ice storage based air-conditioning system is shown in Figure 1. The system can be operated both under full-storage and partial storage load leveling operating strategies. The experimental system included an air-cooled water chiller, an ice storage tank, interconnecting piping, controllers (two and three way valves), measuring equipment, and data collection system. The ethylene glycol-water solution of 30 % concentration by weight was used as the heat transfer fluid.

338 m long, polyethylene coil pipe with 16 mm outside diameter and 2 mm thickness was divided into 26 parts and each part (13 m long) was wounded to form a coil.

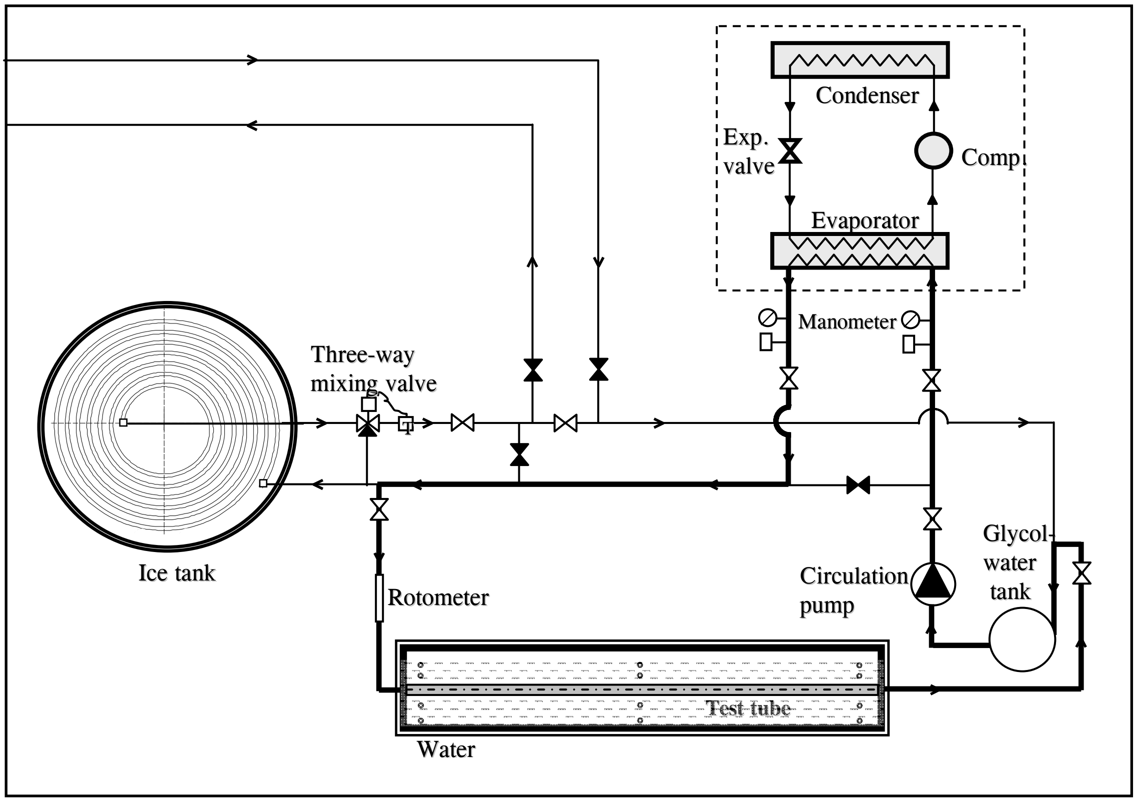



**Figure 1.** Schematic view of experimental test rig

The coils were placed into a circular polyethylene tank having a diameter of 1 m and an overall height of 1.5 m. Charging and discharging tests were carried out to determine the performance of the system constructed.

The experiments of Fertelli et al. (2006 and 2008) showed that mechanisms observed during the ice formation (supercooling, nucleation, and dendritic ice formation) are very important parameters for system performance and they should be investigated in detail. A parallel experimental system was constructed to understand solid-liquid phase change heat transfer phenomena around a tube.

In this study, phase change phenomena around a horizontal tube were investigated both experimentally and analytically. An experimental investigation was carried at three different heat transfer fluid inlet temperatures in order to study the dynamic behavior of ice layer formation on tube. A mathematical model was also developed the heat transfer process for phase change phenomenon around a horizontal tube.

## EXPERIMENTAL SYSTEM

As seen in Figure 1, experimental unit consists of a test tube for ice formation, an air-cooled water chiller unit, a pump, piping, control valves and measurement system. To simulate the conditions in ice-on-coil type ice storage tank, the test tube is made of polyethylene pipe with 16 mm outside diameter, 2 mm thickness and 4 m long. It was placed inside a rectangular vessel of 64 mm wide, 75 mm high and 4000 mm long. The vessel was built from transparent acryclic plates of 4 mm thick, to be able to take photographs of solidification process around the tube. The vessel was filled with tap water to a depth of 50 mm and insulated from all sides including its cover, by 5 cm thick elastomeric rubber foam layer to reduce the heat transfer through the walls.

Ethylene glycol-water solution was used as the heat transfer fluid. It is cooled in the evaporator of the air-cooled water chiller unit and pumped to the test section passing through a valve, which is used for flow rate adjusment, and a rotameter. Temperature of the ethylene glycol-water solution entering into the test section was kept constant at the desired level using a control system, which is constituted of motorized two and three way valves and temperature sensors. Flow rate of the transfer fluid was measured using a rotometer located upstream of the test section. Two thermocouples were used to measure the inlet and the outlet temperatures of the heat transfer fluid. Totally 20 thermocouples were replaced into water at 7 different axial positions (Figure 2) along the test tube for detecting variation of the water temperature in the vessel One thermocouple was utilized at each measuring station except the first (x/L=0.1), the middle (x/L=0.47) and the last (x/L=0.86) ones. 8 thermocouples were used at the first and the last stations, while 4 thermocouples were used at the middle one (Figure 3) to be able to detect the water temperature variation at these cross sections in detail. Ambient air temperature was also monitored using a thermocouple.

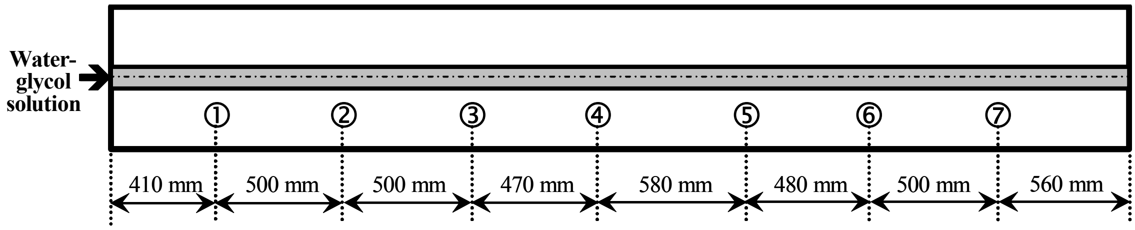
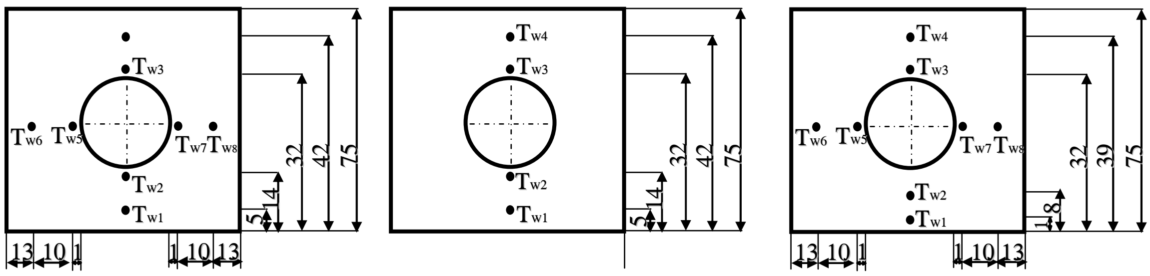



**Figure 2.** Measurement stations along test tube




**a)** x/L= 0.1 **b)** x/L= 0.47 **c)** x/L= 0.86

**Figure 3.** Temperature measurement locations within the water

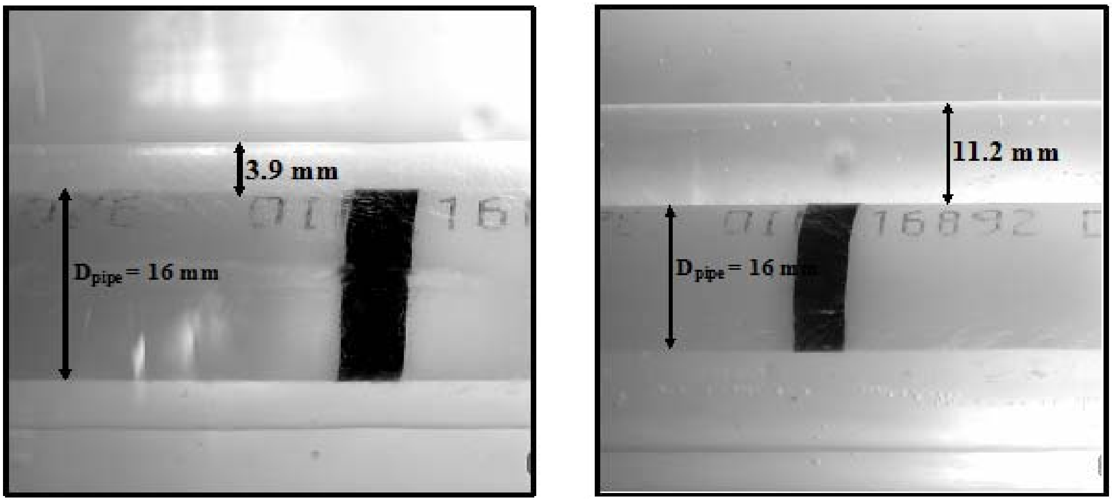
All the thermocouples used were K type, teflon insulated thermocouples. An ice-bath was employed as the reference junction for all the thermocouples used. Outputs of the thermocouples were monitored continuosly with a sampling rate of 30 readings/s, using a computer-controlled data logging system.

Due to the experimental nature of the present work, care was given to the uncertainty in measurements. The fluid flow rate is measured by means of a calibrated rotometer with accuracy of ± 4%. To perform calibration of the rotometer, water was pumped from a supply reservoir to a constant head reservoir. From there, water flowed to a weighing tank through the measuring section with the rotometer under test. The flow rate was adjusted with a control valve situated at the downstream end of the test section. The rotometer was calibrated by measuring the volume of water that passes the rotometer during a certain measuring time.

**Table 1.** Uncertanity and range for different parameters

| Parameter | Range | Uncertainity |
|---|---|---|
| Tube inner radious (mm) | 6 | ± 0.1 mm |
| Tube outer radious (mm) | 8 | ± 0.1 mm |
| Tube length (m) | 0 – 4 | ± 0.5 cm |
| Flow rate (l/h) | 0 – 1000 | ± %4 |
| Temperature (ºC) | -7 to 30 | ± 0.3 ºC |
| Ice thickness (mm) | 0 – 20 | ± 0.1 mm |

Hereto the water was collected in the weighing tank, whereby the volume increment was measured and average flow rate was computed by dividing the volume by the time. Temperatures of water and transfer fluid are measured by means of K type teflon insulated thermocouples with accuracy ± 0.3 ºC. The thermocouples were calibrated against a platinum resistance thermometer in a stirred liquid bath whose temperature was adjusted with the help of a temperature-measuring bench. Thickness of the ice formed around the tube is measured with ± 0.1 mm. Table 1 shows the range and uncertainity of parameters for the experiments. Thickness of the ice formed on the tube was determined using a visual technique. Ice thickness was measured at the same stations where temperature measurements were made. Small observation windows are opened through the insulation material at the measuring stations to be able to make ice thickness measurements. Photographs of the ice were taken with a digital camera (Nikon Coolpix 8700, 8MP, 10x optic zoom) from the front and the top of the vessel at each station to be able to detect circumferential changes in ice thickness. Different light sources and positions were tested during the prelimenary experimets to determine the best lighting arrangement. A traversing mechanism was designed to be able to detect the ice formation along the tube with a short period of time between the stations. The time period between any two measuring station was 20 s at maximum. All photographs were taken in close-up mode with 5 MP resolution. Figure 4 shows two images of solidification taken at two different times at the first measuring station (x/L=0.1) for an inlet temperature of -5.8 ºC, flow rate 900 l/h as an example to the images taken during the experimets. At the end of experiments, the photographs taken were transferred to an image analysis program (Image-ProPlus 4.5) for post processing. Using some of the techniques offerred by the program, bright images that clearly indicate the boundaries of the ice formed around the tube were obtained. From the images processed, thickness of the ice was determined for the top and bottom of the pipe separately (left and right sides of the pipe for the photographs taken from the top of the pipe) using the pipe diameter as a reference dimension.




*(a)* *(b)*

**Figure 4.** Photographs of the ice formed around test tube at two different times (*a*:3000, *b*:11900 s)

## MATHEMATICAL MODEL

Results of the experiments carried out revealed that, temperature of the heat transfer fluid flowing through the tube ($T_f$) does not change too much between the tube inlet and exit. Therefore, it can be assumed constant (Figure 5). Because tube wall is thin and thermal conductivity is not high, the heat transfer between ice-water surface and fluid flowing in the tube can be assumed as one-dimensional.

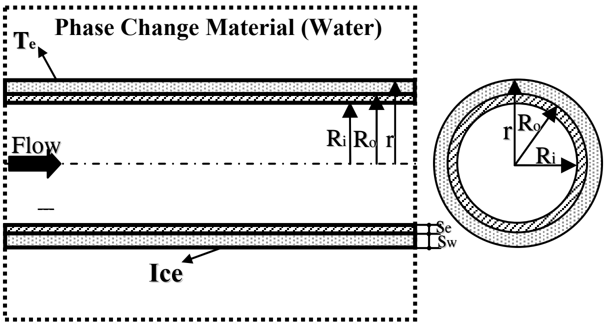



**Figure 5.** Schematic of ice formation process

At an axial position of the tube, the amount of heat transferred per length of the tube ($\dot{Q}_x$) can be calculated from;

$$\dot{Q}_x = \frac{T_e - T_f}{R_p} \quad (1)$$

where $T_e$ is the temperature of the ice and $R_p$ is thermal resistance based on the peripheries, instead of the surface areas:

$$R_p = \frac{1}{h_i P_i} + \frac{s_w}{k_w P_{wm}} + \frac{s_e}{k_e P_{em}} \quad (2)$$

in which $k_w$ and $k_e$ are the thermal conductivities of the tube material and ice, respectively. $h_i$ is the convective heat transfer coefficient inside the tube. The peripheries ($P_i$, $P_{wm}$ and $P_{em}$) are obtained from the following equations:

$$P_i = 2\,\pi\,R_i \quad (3)$$

$$P_{wm} = \frac{2\,\pi\,(R_o - R_i)}{\ln \frac{R_o}{R_i}} \quad (4)$$

$$P_{em} = \frac{2\,\pi\,s_e}{\ln\left(\frac{R_o + s_e}{R_o}\right)} \quad (5)$$

Defining

$$R_{po} = \frac{1}{h_i\,P_i} + \frac{s_w}{k_w\,P_{wm}} \quad (6)$$

$$r = R_o + s_e \quad (7)$$

and

$$R_p^* = R_p / R_{po} \quad (8)$$

$$R_{po}^* = 2\,\pi\,k_e\,R_{po}\,R_o \quad (9)$$

$$r^* = r / R_o \quad (10)$$

the following equation is obtained from eq. (2):

$$R_p^* = 1 + \frac{\ln r^*}{R_{po}^*} \tag{11}$$

Similar to the heat transfer from ice-water surface to flowing fluid in the tube, heat is also transferred from ambient to the ice-water surface. The heat gain ($\dot{Q}_g$) per length of the tube can be written as:

$$\dot{Q}_g = \frac{T_a - T_e}{R_a} \tag{12}$$

Here $T_a$ and $R_a$ are ambient temperature and thermal resistance based on periphery between ambient and ice-water surface, respectively. The outer surface of the vessel is insulated to minimize heat gain ($\dot{Q}_g$) from the ambient. $R_a$ can be calculated from:

$$R_a = \frac{s_i}{k_i\, P_{mi}} + \frac{s_p}{k_p\, P_{mp}} + \frac{1}{h_{ci}\, P_{ic}} + \frac{1}{h_a\, P_a} \tag{13}$$

where $h_a$ is the heat transfer coefficent between ambient and outer surface of the vessel and $h_{ci}$ is heat transfer coefficient between water in the vessel and inner surface of the vessel. $s_p$ and $k_p$ are the thickness and thermal conductivity of the plexiglas, respectively. $P_{mp}$ is the mean periphery of the plexiglas. $P_{ic}$ and $P_a$ are the inner and outer peripheries of the vessel, respectively. $s_i$ and $k_i$ are the thickness and thermal conductivity of the insulation. $P_{mi}$ is the mean periphery of the insulating material. The difference between $\dot{Q}_x$ and $\dot{Q}_g$ is used for ice production, because the temperature difference between fluid ($T_f$) and ice-water surface temperature ($T_e$) is so low that sensible heat storage of ice can be neglected compared with the latent heat of freezing. Therefore, one can write the following equation;

$$\left(\dot{Q}_x - \dot{Q}_g\right) dt = \rho_e\, h_{ew}\, 2\,\pi\, r\, dr \tag{14}$$

where $\rho_e$ is the density of the ice, $h_{ew}$ is the latent heat of freezing of water and t is the time. Using eqs. (1), (12) and (14), the following equation is obtained:

$$dt = \frac{2\,\pi\, h_{ew}\, r\, dr}{\dfrac{T_e - T_f}{R_p} - \dfrac{T_a - T_e}{R_a}} \tag{15}$$

Utilizing the following definitions,

$$t^* = t\, \frac{T_e - T_f}{2\,\pi\, \rho_e\, h_{ew}\, R_o^2\, R_{po}} \tag{16}$$

$$R_a^* = \frac{R_a}{R_{po}}\, \frac{T_e - T_f}{T_a - T_e} \tag{17}$$

the following dimensionless differential equation (18) is found:

$$dt^* = \frac{R_p^*\, r^*\, dr^*}{1 - R_p^* / R_a^*} \tag{18}$$

Because of the insulation, $R_a^*$ should be very big compared with $R_p^*$. Therefore eq. (18) can be rewritten as:

$$dt^* = \left( R_p^* + \frac{R_p^{*\,2}}{R_a^*} \right) r^*\, dr^* \tag{19}$$

Inserting eq. (11) into eq. (18) yields:

$$dt^* = \left[ 1 + \frac{1}{R_a^*} + \frac{1}{R_{po}^*}\left(1 + \frac{2}{R_a^*}\right) \ln r^* + \frac{\left(\ln r^*\right)^2}{R_a^*\, R_{po}^{*\,2}} \right] r^*\, dr^* \tag{20}$$

With the integration of this equation with the boundary condition,

$$t^* = 0 \qquad : \qquad r^* = 1 \tag{21}$$

the following equation is obtained:

$$t^* = \left(1 + \frac{1}{R_a^*}\right)\left(\frac{r^{*2} - 1}{2}\right) + \frac{r^{*2}\left(\ln r^*\right)^2}{2\, R_a^*\, R_{po}^{*\,2}} + \frac{1}{2\, R_{po}^*}\left[\left(1 + \frac{2}{R_a^*}\right) - \frac{1}{R_a^*\, R_{po}^*}\right] \left[ r^{*2}\left(\ln r^* - \frac{1}{2}\right) + \frac{1}{2}\right] \tag{22}$$

Ice thickness $s_e$ can be made dimensionless with

$$s_e^* = s_e / R_o \tag{23}$$

Therefore, the following equation can be written using eq. (10):

$$r^* = 1 + s_e^* \tag{24}$$

## RESULT AND DISCUSSIONS

### Experimental Results

Experiments were carried out at a fixed transport medium flow rate of 900 l/h (corresponds to a Reynolds number of 5318 at the tube inlet) and three different inlet temperatures (-4.3 ºC, -4.9 ºC and -5.8 ºC). The temperature of the water inside the vessel was kept between 0 ºC and 1 ºC at the beginning of the experiments to minimize the natural convection effects. As an example to the water temperature measurements, Figure 6 shows time wise variations of the water temperatures at the measurement points inside the vessel for a transfer fluid inlet temperature of -5.8 ºC. Sensible heat is extracted from the water inside the vessel and transferred to the transfer medium.

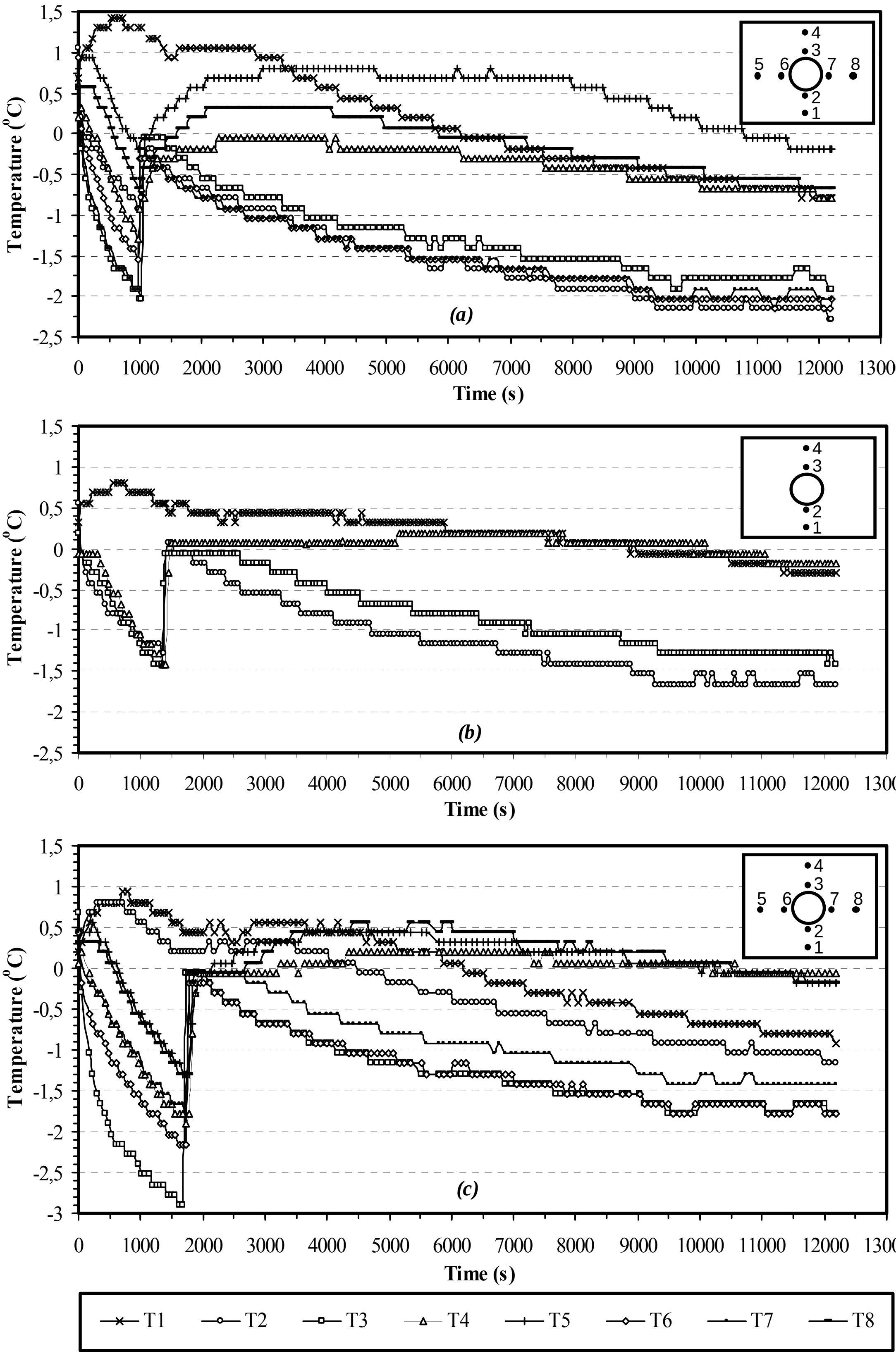



**Figure 6.** Variation of water temperature with time at three measurement stations for $T_{in}$ = -5.8 ºC (a: x/L = 0.1, b: x/L = 0.47, c: x/L = 0.86)

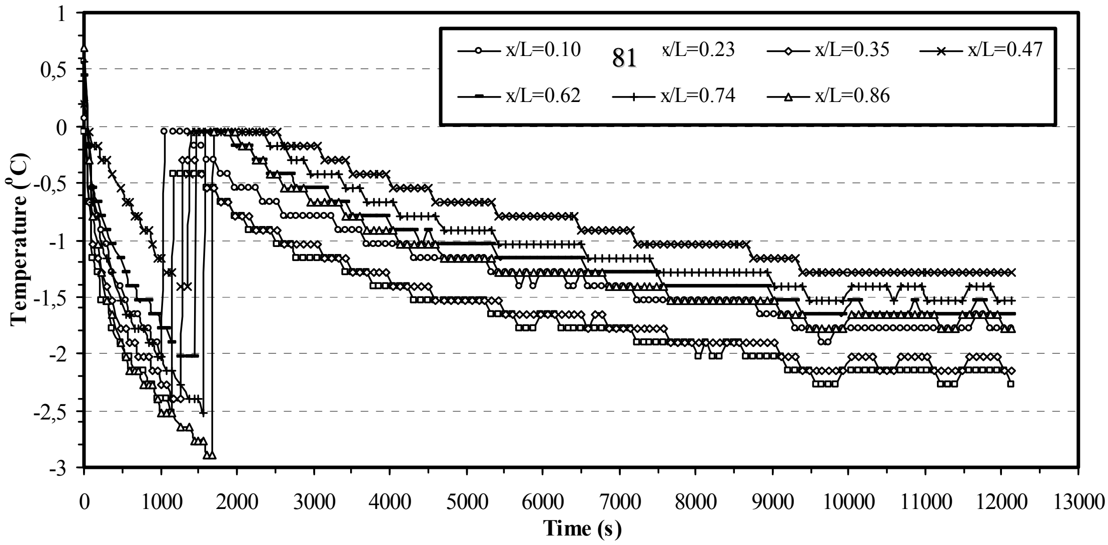



**Figure 7.** Variation of water temperature with time at positions just above the test tube (thermocouple 3) for different axial measurement stations ($T_{in}$ = -5.8 ºC)

As a result, temperature of the water decreases steadily at all measurement points except at the bottom of the tube.

The phase change process does not start at the equilibrium freezing point of water (0 ºC) and temperature of the water decreases below 0 ºC. Cooling continues until the start of nucleation of ice. This process is called as supercooling. Supercooled water is in a metastable liquid state. The maximum possible supercooling ($T_{max}$), which is -38±2 ºC, can be achieved when the water is free of any solid particles that can catalyze ice germ formation (pure water) (Koop, 2004). At about this temperature, freezing happens as a homogeneous nucleation. When the temperature is higher than the limit temperature ($T_{max}$), heterogeneous nucleation occurs. In heterogeneous nucleation, ice grows from crystals that form in the water on freezing nuclei. The ice formed during this stage is called dendritic ice. The degree of supercooling temperature depends on properties of the solid particles inside the fluid. A liquid below its freezing point will crystallize in the presence of a seed crystal or nucleus around which a crystal structure can form. However, lacking any such nucleus, the liquid phase can be maintained all the way down to the temperature at which crystal homogeneous nucleation occurs.

As can be seen from Figure 6, supercooling occurs at all measurement points except the bottom of the tube and the degree of it is between -1.4 ºC and -3 ºC. Once nucleation occurs, a very thin layer of dendritic ice formation starts at the outer surface of the tube in the entrance region (x/L=0.1), and propagates in the axial direction. When the dendritic ice first forms, the temperature rises rapidly to the freezing temperature as a result of the latent heat of fusion of water .

Compared with the supercooling process, duration of this process is very short, lasting only 1 to 3 s, depending on the degree of supercooling and the position.

Dendritic ice formation is followed by latent heat thermal storage process, during which a relatively thick layer of ice starts to form around the tube outer surface. During this period, temperature remains at freezing point temperature (0 ºC) for a certain period of time. However, when the ice is formed, temperature of the ice begins to fall below 0 ºC, due to heat transfer from the water inside the vessel to the heat transfer fluid (cooling of ice). Temperature decrease can be clearly observed when the measuring point (thermocouple) is covered by the ice (thermocouples 2, 3, 6 and 7 in Figure 6a).

Temperature of the water never decreases down to freezing temperature (0 ºC) at the bottom of the vessel (thermocouples 1 and 2) during ice formation. The slight temperature increase at the beginning of the experiment is due to collection of warm water at the bottom of the vessel.

The same processes can also be seen from Figure 7 that shows the variation of water temperature with time near the tube wall (thermocouple 3) at different axial positions. Since the thermocouple 3 is located very close to the tube, it is covered by the ice as soon as ice formation starts. Therefore, temperature stays constant at 0 ºC only for a very short period of time.

Variation of the time from the beginning of the experiment to the start of nucleation (nucleation time) along the pipe length is given in Figure 8 for different inlet temperatures of heat transfer fluid. As can be seen from the figure, nucleation first starts at the entrance region, which is the coldest region, and propagates along the tube.

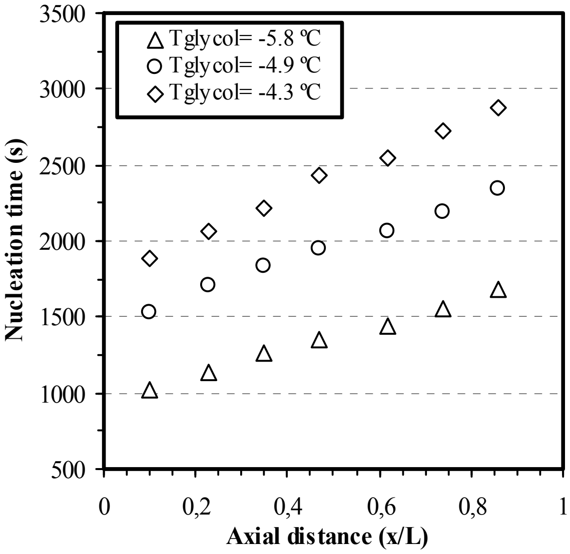



**Figure 8.** Variation of nucleation time along tube for different transfer fluid inlet temperatures

Nucleation time increases almost linearly with the axial distance for all inlet temperatures. It is obvious that fluid inlet temperature seriously affects the onset of the phase change of water and nucleation time. Nucleation time increases with the increase of transfer fluid inlet temperature. Increase of inlet temperature from -5.8 ºC to -4.3 ºC almost doubles the nucleation time at all axial positions along the tube. Due to high fluid inlet temperature, the temperature of water needs more time to reach the nucleation temperature. Similar results were also reported by Chen et al. (2000) who conducted a series of experiments to investigate the supercooling phenomenon and the effect of inlet coolant temperature on the nucleation of water inside cylinder.

The thickness of the ice formed at the bottom, top, right and left sides of the tube was determined at different axial positions during the experiments. As an example to the measurements, Figure 9 shows time wise variations of the ice thickness at three axial positions (x/L=0.1, 0.47 and 0.86) for a transfer fluid inlet temperature of -5.8 ºC. Photographs of the ice formation from the top of the tube were not suitable for the post processing because of dense dendritic ice formation at the beginning of the experiments at the top of the tube.

Similar trends are observed at all measuring stations along the tube. At the beginning of the ice formation, thickness of the ice is almost equal around the tube. Ice formation is then better at the upper part of the tube than the lower part of the tube. This is because of heat transfer from outside, although the vessel is insulated properly. As result of heat gain from outside, warm water is collected at the bottom and the cold water is collected at the top. The difference between the top and the bottom of the tube in terms of the ice thickness is approximately constant (0.6 mm) after 3000 s. The thickness of the ice at the right and left sides of the tube is close to each other.

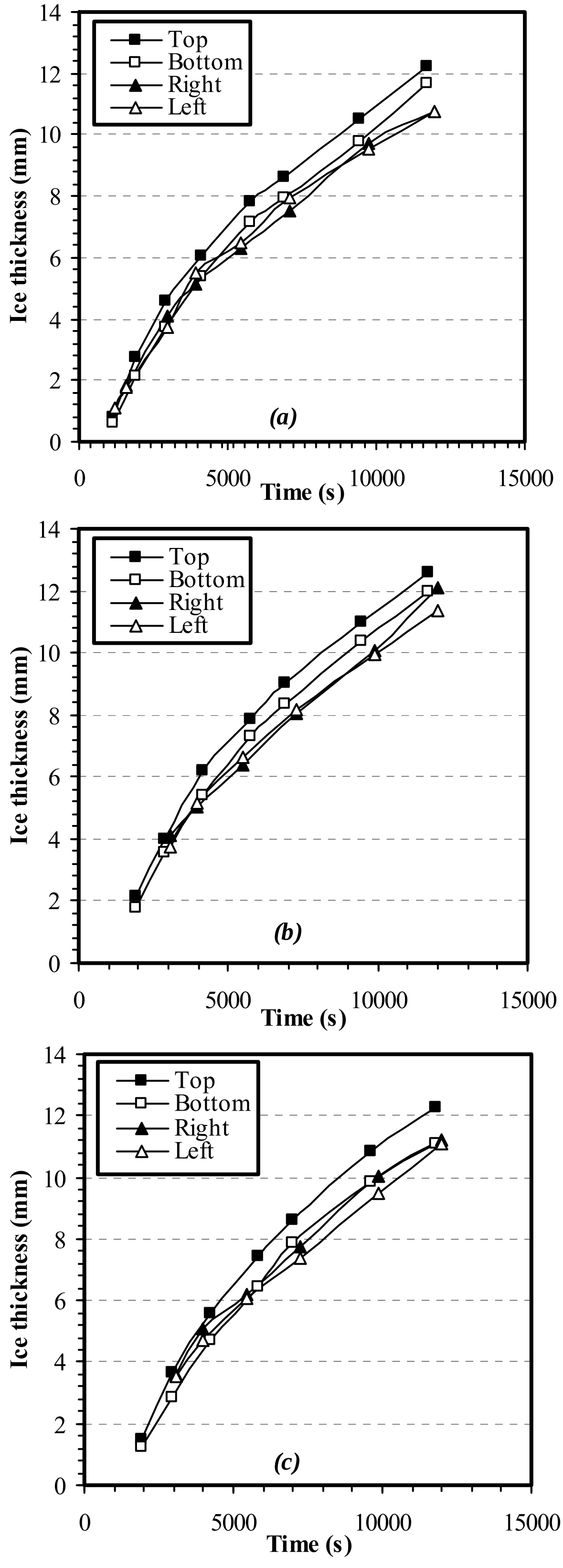



**Figure 9.** Variation of ice thickness with time for top, bottom and sides of tube for $T_{in}$ = -5.8 ºC (a: x/L= 0.1, b: x/L= 0.47, c: x/L= 0.86)

The shape of the ice formation during the experiments at three axial positions (x/L=0.1, 0.47 and 0.86) is depicted in Figure 10 for three different transfer fluid inlet temperatures (-4.3 ºC, -4.9 ºC and -5.8 ºC).

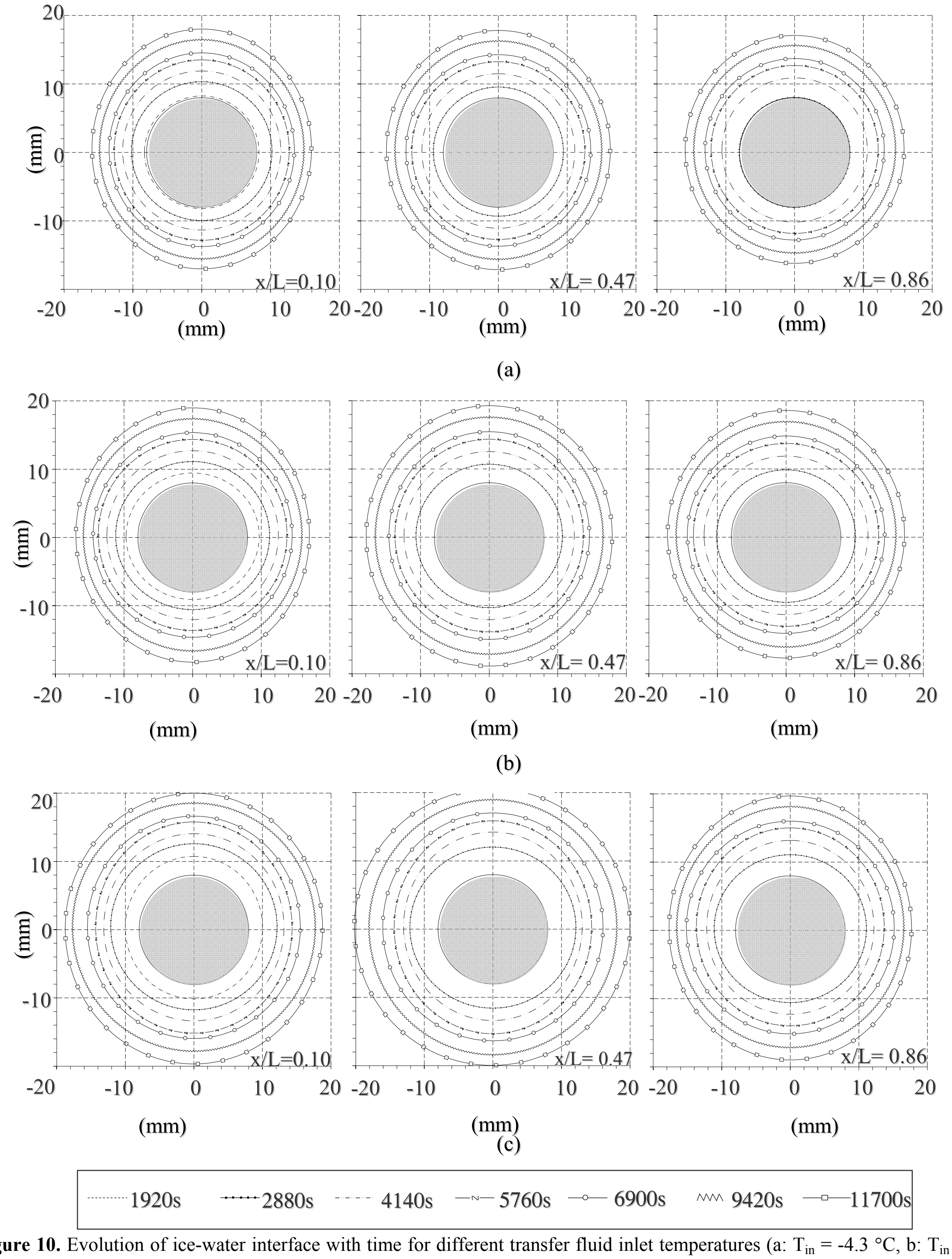



**Figure 10.** Evolution of ice-water interface with time for different transfer fluid inlet temperatures (a: $T_{in}$ = -4.3 °C, b: $T_{in}$ = -4.9 °C, c: $T_{in}$ = -5.8 °C)

When the ice forms first, it has almost a circular shape. However, the shape is distorted in later stages of ice formation. Ice thickness at the top becomes higher than the bottom, right and left, and therefore, the shape takes an oval form.

Influence of transfer fluid inlet temperature on ice thickness is shown in Figure 11 for 3 different times during the experiments (2880 s, 6900 s and 11700 s) at an axial position of x/L=0.47. With the increase of transfer fluid inlet temperature, ice thickness decreases at all points around the tube. The same trend is also observed at other axial positions. As discussed above, ice formation is almost uniform around the tube at the initial stages of ice formation (2880 s). However later the uniformity is distorted and a clear difference between the top and bottom is observed at 11700 s.

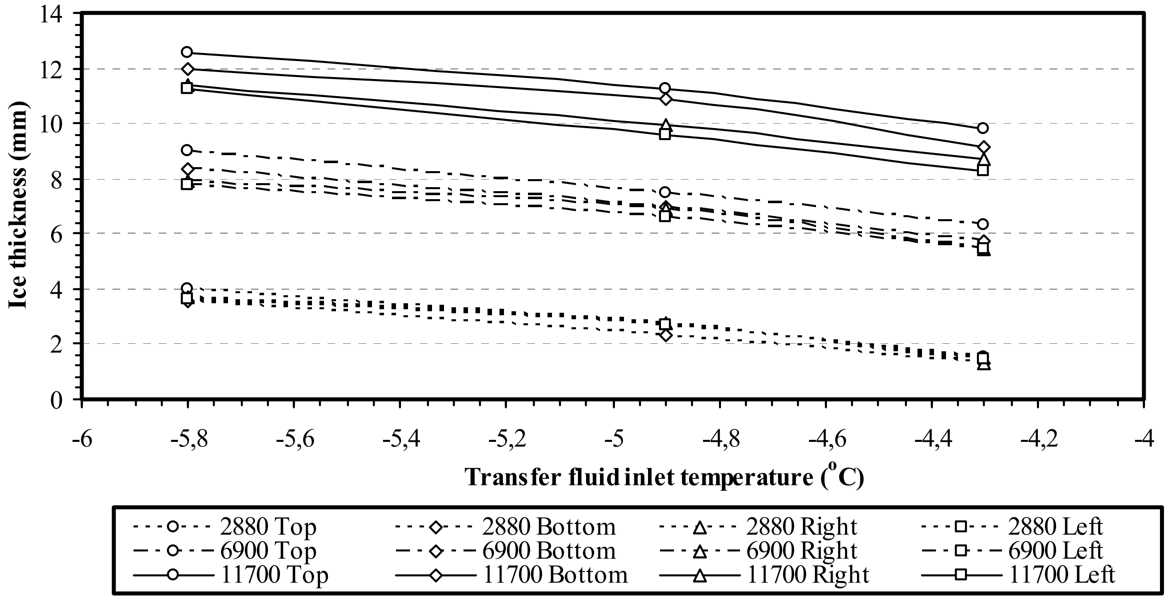
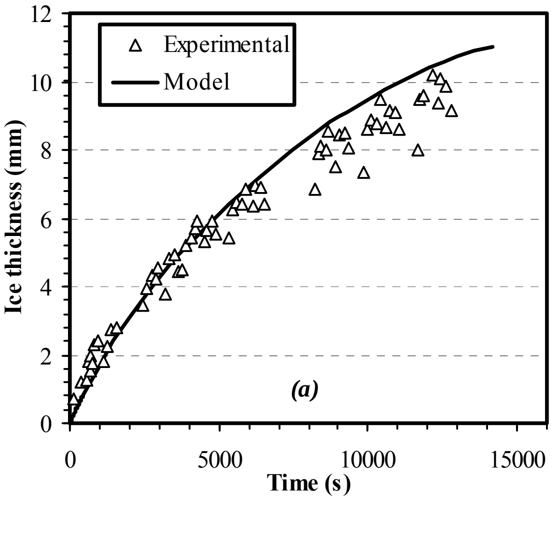



**Figure 11.** Influence of transfer fluid inlet temperature on ice thickness at x/L= 0.47

**Comparison of Mathematical Model with Experimental Results**

A simple model for the formation of ice around a cylindrical tube is given above. Comparison of the model and experimental results are given in Figure 12 for three different transfer fluid inlet temperatures (-4.3, -4.9 and -5.8 ºC) which corresponds to $R_a^* = 3.866$, $R_a^* = 4.566$ and $R_a^* = 5.238$, respectively. The value of $R_{po}^*$ is 1.912 for the experiments. The experimental values shown in this figure were obtained by averaging ice thickness values determined at top, bottom, right and left of the tube at each axial position. Since the time scale starts from the formation of ice in the model, the experimentally obtained values at different axial positions were shifted according to time at which ice formation starts at the axial position of interest. Therefore, time scale in Figure 12 is not the absolute time scale, rather represents the time passed from the start of ice formation. The figure shows the experimental ice thicknesses at all axial positions with shifted time scales.



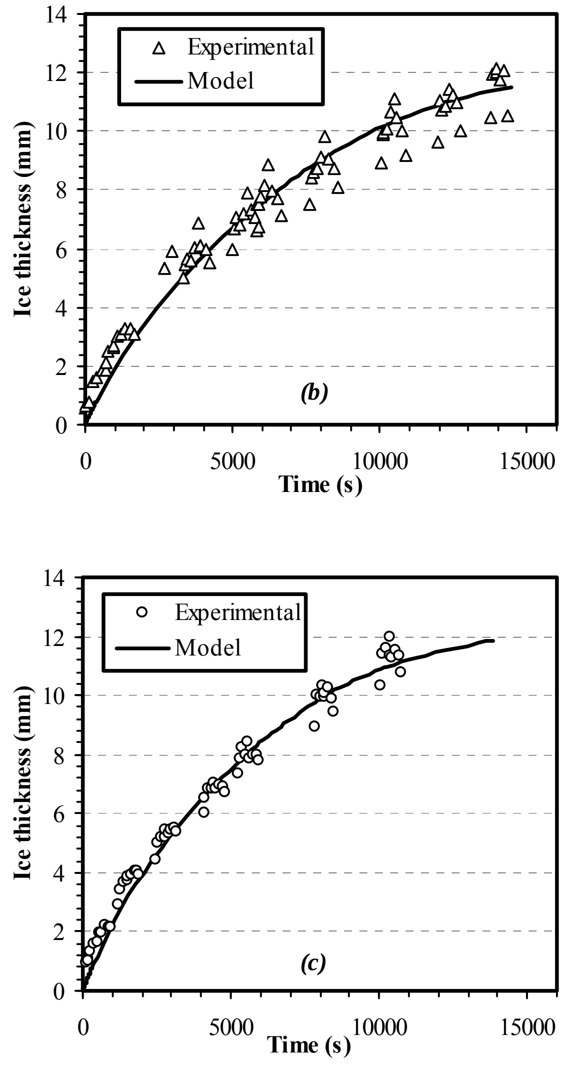




**Figure 12.** Comparison of ice thickness obtained from measurements and model for different transfer fluid inlet temperatures (a: $T_{in}$ = -4.3 °C, b: $T_{in}$ = -4.9 °C, c: $T_{in}$ = -5.8 °C)

As can be seen from Figure 12, the agreement between the model and the experimental values is good during the ice formation process for all transfer fluid inlet temperatures. The model under predicts slightly ice thickness at the beginning of the process and over predicts at the end.

## CONCLUSION

In the present study, phase change phenomena and the effect of heat transfer fluid temperature on ice formation around a horizontal tube in a rectangular vessel were investigated both experimentally and analytically. Based on the obtained results our conclusions are summarized as follows:

1. Experimental results show that supercooling occurs at all axial measuring stations along the tube and nucleation first starts at the entrance region and propagates along the tube. Nucleation temperatures for all measurement points are between -1.4 ºC and -3 ºC.
2. It is obvious that the heat transfer fluid inlet temperature seriously affects the onset of the phase change of water and nucleation time. With the decrease of heat transfer fluid inlet temperature, nucleation time decreases. Furthermore nucleation time increases with the axial distance for all heat transfer fluid inlet temperatures.
3. The thickness of the ice formed at the top and bottom sides of tube is different from each other, although the thickness of the ice formed at the right and left sides is close to each other. Ice thickness around tube is substantially influenced by natural convection that occurs within the water. With the increase of transfer fluid inlet temperature, ice thickness decreases at all points around the tube.
4. Ice thickness evaluated by mathematical model agrees reasonably with the experimental data for all transfer fluid inlet temperatures.

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