A Numerical and Experimental Investigation into the Melting of Ice Around a Horizontal Cylinder

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ABSTRACT

A Combined numerical and experimental problem of outward melting of ice around isothermal horizontal cylinder is studied. In theoretical work, a finite volume is used to discretize transient heat transfer energy equation in cylindrical geometry with cylindrical coordinates. The Line Successive Over Relaxation (LSOR) method is used to solve the discretized energy equation. An enthalpy scheme is proposed to convert the energy equation into non-linear equation with the Enthalpy (E). In the experimental work, an apparatus was built to estimate ice solidifying and melting around a horizontal cylinder and the temperature was measured around a horizontal cylinder in PCM. Numerical results of the enthalpy method were compared with experimental results and gave results in acceptable agreement. The difference is attributed to the negligence of the natural convection in theoretical calculations. The other reason is the assumption of one-dimensional distribution in the calculation of flowing fluid bulk temperature.

Keywords: Ice melting, Horizontal Cylinder, Enthalpy Method.

1. INTRODUCTION

Transient heat-transfer problems involving melting or solidification generally referred to, as “phase-change or moving-boundary” problems are important in many engineering applications. Examples are: welding, casting, thermal energy storage units using phase change materials, manufacture of frozen food, melting and freezing of snow around pipes, heat pipe start-up from the frozen state, etc. The solution of phase-change problems is inherently difficult because the interface between the solid and liquid phases which moves as the latent heat is absorbed or released at the interface; as a result the location of the solid-liquid interface is not a known priori and must follow as a part of the solution (Necati Ozisik, 1980).

Little research is done on multiple phase front problems, especially in cylindrical systems. Numerous authors have addressed problems involving phase change. (Cao and Faghri, 1989) studied the numerical analysis of Stefan problems for generalized multi-dimensional phase-change. (Vick, Nelson and Yu, 1998) addressed freezing and melting with multiple phase fronts along the outside of tube. (Lamberg, Lehtinieme and Henell, 2002) investigated numerically and experimentally the problem of melting and freezing processes in phase change material storage. (Antwan, 2001) solved the enthalpy method with a body fitted coordinate system of three-dimensional with phase change. (Shamsundar, 1982; Ho and Chen, 1986; Vargas, Benjan and Dobrovicescu, 1994) studied the unsteady state of ice melting/freezing around a horizontal cylinder, and (Souza Mendes and Pinho Brasil, 1987) studied melting around an isothermal vertical cylinder.

2. FORMULATION OF THE PROBLEM

Figure (1) illustrates the physical problem of ice undergoing an outward melting process around a horizontal isothermal heated cylinder, by a fluid flowing through a long cylinder surrounded by a Phase-Change Material PCM (ice). A pure substance (PCM) with a freezing and melting temperature initially at its melting temperature $T_m$ is contained between two concentric cylindrical walls of length L. The thin outside wall is insulated. There is a fluid of bulk temperature $T_b(z,t)$ and...
a mass flow rate of \( m(t) \) flowing inside the cylinder. The fluid enters the cylinder at a constant temperature of \( T_{\text{in}} \) \( \Rightarrow T_\text{m} \) and leaves the cylinder at \( T_{\text{out}} \). Melting is started by suddenly raising the temperature of the inner cylinder to the specified temperature \( T_i > T_m \). This causes layers of liquid forms and propagates from inner wall cylinder outward to outer cylinder. This situation is encountered in thermal energy storage systems. The change in volume due to ice melting was neglected.

**Figure (1) A typical tube showing details of boundary.**

Mathematically, the process of solid-liquid phase change is characterized by the existence of time dependent moving phase change boundary, which is described by a function of a three dimensions in polar coordinate and time \( t, S(r, \theta, z, t) \). From the foregoing section, it is concluded that the ice melting around horizontal cylinder is governed by the normalized partial differential non-linear energy equation in 3-dimensional cylindrical coordinate.

In this paper the main aim is to study the melting process in the ice storage systems. The work is done in two parts; numerical and experimental. In the theoretical part, a numerical analysis with a control finite volume is used with simple strategy proposed to transform the energy equation into a non-linear equation with a single dependant variable \( E \). Thus, solving a phase-change problem is equivalent to solving a non-linear enthalpy equation, and existing algorithms are readily applicable with some modification.

2.1 Temperature Distributions across the Wall of the Inner Cylinder

The method to be used in the solution of the heat transfer problem in the three regions of the transformed domain is the finite volume method according to Patankar (1980). The time-dependent problems, the conservation law for the transport of a scalar in an unsteady flow with neglecting convection term has the general form (Versteeg and Halalasekera, 1995).

\[
\frac{\partial}{\partial t} \left( \rho \ c_p \ T \right) = \nabla \left( \Gamma \ \nabla T \right) + S_T \quad \cdots (1)
\]

Unsteady three-dimensional cylinder coordinate heat conduction is governed by the equation:

\[
\rho \ c_p \ \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r k \ \frac{\partial T}{\partial r} \right) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} \left( k \ \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( k \ \frac{\partial T}{\partial z} \right) \quad \cdots (2)
\]

A portion of a three-dimensional grid is shown in Figure (2). For the grid point \( P \), points \( N \) and \( S \) (denoting North and South) are its \( r \)-direction neighbors. Points \( E \) and \( W \) (denoting East and West) are its \( \theta \)-direction neighbors while points \( T \) and \( B \) (denoting Top and Bottom) are its \( z \)-direction neighbors. Dashed lines show the control volume around point \( P \).

**Figure (2) Control volume in three-dimensional cylindrical coordinates.**

Multiplying Equation (2) by \( r \) with integration over the control volume and over a time interval from \( t \) to \( t + \Delta t \) gives.

\[
\int_{t}^{t+\Delta t} \left[ \int_{c_v} \rho \ c_p \ \frac{\partial T}{\partial t} \right] \ dV \ dt \quad \cdots (3)
\]

Identifying the coefficient of \( T_N \), \( T_E \), \( T_W \), \( T_T \) and \( T_B \) as \( a_N \), \( a_S \), \( a_E \), \( a_W \), \( a_T \) and \( a_B \) and the descretized of Equation (3) in the familiar standard explicit form:
2.2 Enthalpy Transformation of the Energy Equation

The three-dimensional energy equation governing with no viscous dissipation, neglecting convective term incorporated with the incorporation of the continuity equation in the cylindrical coordinate system is:

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( rp_k \frac{\partial T}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( k \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) = \frac{\rho}{c_p} \frac{\partial E}{\partial t} \quad \ldots (8) \]

With the state equation

\[ C_p = \frac{dE}{dT} \quad \ldots (9) \]

In the case of constant specific heats for each phase, phase change occurs at a single temperature:

\[ T = \begin{cases} T_m + E / C_s & E \leq 0 \\ T_m & 0 < E < H \\ (E - H) / C_l & E \geq H \end{cases} \quad \ldots (10) \]

Where \( T_m \) is the melting or freezing temperature. In the above relation, \( E = 0 \) was selected corresponding to phase-change materials in their solid state to temperature \( T_m \).

The "Kirchhoff" temperature is introduced as follows (Holman, 1989).

\[ T^* = \int_{r_0}^r k(\eta) d\eta = \begin{cases} k_s(T - T_m) & T < T_m \\ 0 & T = T_m \\ k_s(T - T_m) & T > T_m \end{cases} \quad \ldots (11) \]

Transforming Equation (10) to the definition given in Equation (11) results in:

\[ T^* = \begin{cases} k_s E / C_s & E \leq 0 \\ 0 & 0 < E < H \\ k_s(E - H) / C_s & E \geq H \end{cases} \quad \ldots (12) \]

and multiplying Equation (8) by \( r \) becomes,

\[ \frac{\partial}{\partial r} \left( \frac{r \partial T^*}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{r \partial T^*}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \frac{r \partial T^*}{\partial z} \right) = r \frac{\partial E}{\partial t} \quad \ldots (13) \]

Now, let us introduce an enthalpy function as follows:

\[ T^* = \Gamma(E) E + S(E) \quad \ldots (14) \]

For the phase change occurring at a single temperature,

\[ \Gamma(E) = \begin{cases} k_s / C_s & E \leq 0 \\ 0 & 0 < E < H \\ k_s / C_s & E \geq H \end{cases} \quad \ldots (15) \]

and

\[ S(E) = \begin{cases} 0 & E \leq 0 \\ 0 & 0 < E < H \\ -Hk_s / C_s & E \geq H \end{cases} \quad \ldots (16) \]

Substituting Equation (14) with Equation (13), the following is noticed:

\[ \frac{\partial}{\partial r} \left( \frac{r \partial T^*}{\partial r} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{r \partial T^*}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \frac{r \partial T^*}{\partial z} \right) = r \frac{\partial (\Gamma E + S)}{\partial t} \quad \ldots (17) \]

Then

\[ \rho \frac{\partial}{\partial t} \left( \frac{r \partial E}{\partial t} \right) + \frac{1}{r} \frac{\partial}{\partial \theta} \left( \frac{r \partial (\Gamma E)}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( \frac{r \partial (\Gamma E)}{\partial z} \right) + p \quad \ldots (18) \]

With
Using an explicit scheme and referring to Figure (2), the left hand side becomes
\[
\iint \rho \frac{\partial E}{\partial t} \Delta V = \rho \Delta V \left( \frac{E_p - E_p^o}{\Delta t} \right) \quad \text{(25)}
\]

The first term of r-direction from the right hand side of Equation (24) becomes:
\[
\iint \frac{\partial}{\partial r} \left( \frac{\rho \Gamma(E)}{\partial r} \right) \Delta V = \left[ \frac{r \partial E}{\partial r} \right] \Delta \theta \Delta z
\]

\[
= \frac{r \Delta \theta \Delta z}{\delta r_p} \left( E_{n1} - E_{p1} \right) - \frac{r \Delta \theta \Delta z}{\delta r_s} \left( E_{p2} - E_{s2} \right) \quad \text{(26)}
\]

and
\[
\iint \frac{\partial}{\partial r} \left( \frac{\rho \Gamma(E)}{\partial r} \right) \Delta V = \left[ \frac{r \partial E}{\partial r} \right] \Delta \theta \Delta z
\]

\[
= \frac{r \partial E}{\partial r} \left( S_n - S_p \right) - \frac{r \partial E}{\partial r} \left( S_p - S_s \right) \quad \text{(27)}
\]

The same way followed the second and third terms of \( \theta \) and Z directions.

Now to identify the coefficient of \( E_N, E_S, E_E, E_W, E_T \) and \( E_B \) as \( a_N \), \( a_S \), \( a_E \), \( a_W \), \( a_T \), and \( a_B \) and Equation (24) is written in the familiar standard form to become
\[
a_p^o E_p = a_N E_N^o + a_S E_S^o + a_E E_E^o + a_W E_W^o + a_T E_T^o + a_B E_B^o + b
\]

With \( E^o \) denoting the old value of \( E \) at grid point \( P \), the values of coefficient are:
\[
a_N = \frac{r_s \Gamma_N \Delta \theta \Delta z}{\delta r_s}, \quad a_S = \frac{r_s \Gamma_S \Delta \theta \Delta z}{\delta r_s}, \quad a_E = \frac{r_s \Gamma_E \Delta r \Delta \theta}{\delta \theta_s}
\]

\[
a_W = \frac{r_s \Gamma_W \Delta r \Delta \theta}{\delta r_w}, \quad a_T = \frac{r_s \Gamma_T \Delta r \Delta \theta}{\delta \theta_T}, \quad a_B = \frac{r_s \Gamma_B \Delta r \Delta \theta}{\delta \theta_B}
\]

\[
\text{Where}\quad a_p = \frac{\rho \Delta V}{\Delta t} \quad \text{(30)}
\]
\[ b = \left[ a_N + a_{S} + a_{E} + a_{W} + a_{T} - a_P \right] + b_N S_{N} + b_S S_{S} + b_E S_{E} \]
\[ + b_{W} S_{W} + b_T S_{T} + b_{B} S_{B} \]  

\[ \frac{d_{q}}{d_{r}} = m_{c} c_{p} \left[ T_{b(k)} - T_{b(k-1)} \right] \]  

where subscript \( k \) refers to the local bulk temperature in flow direction (z-direction) and \( g \) refers to the glycol solution. In same differential length \( dz \) the heat added \( dq \) can be expressed either in terms of a bulk-temperature difference or in terms of heat-transfer coefficient

\[ dq = m_{c} c_{p} \left[ \frac{1}{2} \right] \left( T_{w} - T_{b} \text{ (average) } \right) \]  

where

\[ T_{b(average)} = \left( T_{b(k)} + T_{b(k-1)} \right) \]  

... (34)

\[ T_{w} = \left( 1 - F \right) T_{b(k)} \right) + 2 F T_{w} \]  

... (35)

where

\[ F = \frac{\pi}{2} \frac{r_{h} \Delta z}{m_{c} c_{p}} \]  

... (36)

To determine the bulk-temperature, heat transfer coefficient (h) between the flowing fluid and the pipe surface must be calculated.

For turbulent flow

\[ Nu = h D/k = 0.023 Re^{0.8} Pr^n \]  

... (37)

with \( n = 0.4 \) for heating

2.5 Boundary Conditions
a. Inside Surface Pipe Temperature

To estimate the temperature of points on the surface of the inner cylinder, in which fluid flows, the following heat balance equation is used as:

\[ h \Delta T = -k_{pipe} A \frac{dT}{dr} \]  

... (38)

where \( k_{pipe} \) is the conductivity of the pipe, \( A \) is the pipe surface area and \( \Delta T \) is the temperature difference between the wall temperature and the average bulk temperature.

When we refer to figure (4) with the backward difference, the first order derivative of temperature (\( T \)) with respect to radius (\( r \)) is equal to
\[ \frac{dT}{dr} = \left[ T_{i+1,j,k} - T_{i,j,k} \right] \frac{dr}{dr} \]

at \( i=1 \) pipe surface position \( T_w = T_{i,j,k} \)

Thus Equation (38) becomes

\[ \tau_{k,j,k} = \left[ FF \cdot T_{2,j,k} + \left( \left( k \right)^2 T_b \cdot \left[ k \cdot j \right] \right)^2 \right] \left( 1 + FF \right) \]

where

\[ FF = \frac{k_{pipe}}{h \ dr} \]

This is the temperature of the inside pipe surface.

b. Pipe-Ice-Interface

Referring to figure (5) at pipe-ice interface, outer surface temperature and energy balance around control volume is:

\[ dr = \frac{dr_1 + dr_2}{2} \]

\[ d\tau = \frac{dr_1 + dr_2}{2} \]

\[ d\tau = \frac{dr_1 + dr_2}{2} \]

Figure (5) Discretization in pipe-ice interface.

\[ \frac{k_{ice} + k_{pipe}}{2} 2\pi r_{mo2} dr_{n} \left( \frac{T_{mo2,i+1,j,k} - T_{mo2,i,j,k}}{dz} \right) \]

\[ \frac{k_{ice} + k_{pipe}}{2} 2\pi r_{mo2} dr_{n} \left( \frac{T_{i,j+1} - T_{i,j}}{dz} \right) \]

\[ -k_{ice} 2\pi \left( \frac{\eta_{mo2} + \eta_{mo2+1}}{2} \right) dz \left( \frac{T_{mo2,i,j,k} - T_{mo2+1,i,j,k}}{dr_{n}} \right) \]

\[ -k_{pipe} 2\pi \left( \frac{\eta_{mo2} + \eta_{mo2+1}}{2} \right) dz \left( \frac{T_{mo2,i,j,k} - T_{mo2-1,i,j,k}}{dr_{n}} \right) = 0 \]

In the familiar standard

\[ a_{T_{mo2,i,j,k}} = a_{w} T_{mo2,i,j,k+1} + a_{w} T_{mo2,j,k-1} + a_{n} T_{mo2+1,i,j,k} + a_{s} T_{mo2-1,i,j,k} \]

This is the temperature of the outside pipe surface.

Where

\[ a_{w} = \left( \frac{k_{ice} + k_{pipe}}{2} \right) \frac{\eta_{mo2}}{dr_{n}} \]

\[ a_{w} = \left( \frac{k_{ice} + k_{pipe}}{2} \right) \frac{\eta_{mo2}}{dr_{n}} \]

\[ a_{w} = \left( \frac{k_{ice} + k_{pipe}}{2} \right) \frac{\eta_{mo2}}{dr_{n}} \]

\[ a_{w} = \left( \frac{k_{ice} + k_{pipe}}{2} \right) \frac{\eta_{mo2}}{dr_{n}} \]

And

\[ a = a_{w} + a_{n} + a_{s} \]

3. EXPERIMENTAL APPARATUS AND PROCEDURE

For this purpose a test rig was designed to contain a horizontal copper tube inside a glass cylinder with a large diameter to form a concentric cylinder. The two ends of the concentric cylinder were closed with a thick perplex flange sheet to make a sealed container as shown in Figure (6).

The copper test cylinder was (35 mm O.D., wall thickness 1.5 mm, and length 400mm). Copper-constant thermocouples were used for temperature measurement and thirty six thermocouple wires were fixed on the outer surface of copper.

The circulated solution was heated by an electric heater in the ethylene glycol-water solution tank and was controlled to a temperature higher than the fusion temperature of the ice. The melting layer was increased with time. The solid-liquid interface was photographed at different times from the front view (radial-axial) direction in order to show the ice melting thickness by showing the
solid-liquid interface shape and position. A digital still camera type SONY, Model No. DSC-717, Effective 5.0 Mega Pixels.at was used to photograph this process.

4. RESULTS AND DISCUSSION

Figure (7) shows the photographed pictures of melting processes at different time intervals. The layer of water was increased with the increase of the time intervals, location and shape of interface line was transferred in radial direction with increasing the melting time. It was also noticed that the interface line takes a near cone shape from inlet to outlet flow direction. The base of the cone was at the inlet, This was caused by the heat of flowing fluid at the inlet higher than that at the outlet, and was transformed to ice gradually in the flow direction (z-direction).

Figure (8) shows the ice layer and temperature distribution around cylinder in experimental solidification process. Notice that the temperature increases in radial direction and this state will be used as the initial condition for the melting process. The effect of natural convection is also very evident in this stage.

Figures (9) and (10) show the results obtained from the solution of enthalpy method in numerical work for temperature distribution and enthalpy in radial direction plotted as a contour. From these figures, it can be noticed that the location of interface is evident.

Figure (11) shows a comparison between the results of the experimental and numerical solution of temperature distribution in PCM (ice) in radial direction plotted as graphs. Notice that the temperature increases with time interval, at time equal to one hour from melting, the location of the interface is at a distance equal to six millimeters from the outer cylinder surface for the experimental work, but it is lower than this location in the numerical work. This is caused by the effects of natural convection and the properties of the flowing fluid which are assumed to be constant, but in the experimental work they become functions of temperature.

Figure (12) shows a comparison between the experimental and theoretical results in temperature distribution in flow direction (average 12%). Notice that the results are acceptable despite the difference, due to natural convection effect.

Figure (13) shows a comparison between the results obtained from the solution of enthalpy method in numerical calculations for both temperature and enthalpy. Notice that both temperature and enthalpy increase in radial direction with the increase of the melting time intervals. It also shows that the increase in enthalpy is a better description of temperature to find out if the state of phase is liquid or solid.

Figure (14-a) shows the variation in temperature and enthalpy in numerical solution at six millimeter from the outer cylinder surface in radial direction. Notice that both temperature and enthalpy are in solid phase (ice) at time equal to one hour. After this time, the temperature reaches to zero degree and discontinue increasing with the increase of melting time because the latent heat referred to, does not depend on the change of temperature to find out the change of energy, while the enthalpy continues to increase with the increase of melting time to refer to the change of energy.

Results of figures (14-b) and (14-c) at distances of twelve and eighteen millimeters from outer cylinder surface, respectively show the same behavior as in figure (14-a) which needs more melting time to reach the change phase from solid state to liquid state because their positions are in radial direction.

5. CONCLUSIONS

Numerical and experimental simulations have been performed for outward melting of ice around a horizontal isothermal cylinder and the phase change material (ice) is initially at solid phase. Phase change problems in general need a great effort in deriving the governing equations and applying the boundary conditions, due to the distortion shape of the solid and liquid regions.

The finite volume method and enthalpy transforming model proposed in this work, prove to be capable of handling complicated phase-change problems, occurring both at a single temperature and temperature range with fixed grids. Due to the one dependent variable nature of the transformed equation, the diffusion situation can be handled with an appropriate algorithm, while convection situation is neglected. A comparison between experimental and numerical results gives a good agreement, showing that the present model can properly predict the phase-change processes.

An experimental apparatus was built to solidify and melt of the ice around a horizontal cylinder located in the circular bath. From this work the shape of interface appears in photographed pictures and from contour
plotting of temperature distribution. The main conclusions that can be drawn from this work are:

1. The experimental shape of interface differs from that of the theoretical one. In experiment, it has the shape of a cone whose base is at the inlet, while theoretically, it has the shape of a cylinder. This is due to the natural convection effects.

2. In experimental work, the ice melting thickness at the upper position of the cylinder wall is larger than that at the lower position, while in theoretical work the ice thickness is the same for all angular directions. This is also attributed to the natural convection effects.

3. The enthalpy method gives a good result, because the enthalpy continuously changes with time, while the temperature method discontinues because of latent heat. Enthalpy continues to increase with time, but the temperature reaches zero degree and remains unchanged.

4. Comparisons between experimental and numerical results give a good agreement (12%), showing that the present model can properly predict the phase change processes.

NOMENCLATURE

A Area, $m^2$

$\alpha$ Coefficient

$b$ Source term in the discretization equation

$C_p$ Specific heat, J/kg°C

$D$ Diameter, m

$E$ Enthalpy, J/kg

$H$ Latent heat of fusion, J/kg

$k$ Thermal conductivity, W/m°C

$L$ Reference length, m

$N_u$ Nusselt No., $hD/k$

$m$ Mass flow rates, kg/s

$P$, Prandtl No., $\mu/\rho$

$q$ Heat flux, W/m$^2$

$r$ Radius, m

$R_e$ Reynolds No., $\rho u D/\mu$

$T$ Temperature, °C

$T_i$ Initial temperature, °C

$T_m$ Melting temperature, °C

$T_w$ Wall temperature, °C

$T^*$ "Kirchhoff " temperature, °C

$\Delta T$ Temperature range, °C

$\Delta r$ r-direction width of the control volume

$\Delta \theta$ $\theta$-Direction width of the control volume

$\Delta z$ z-Direction width of the control volume

$S$ Source term

$t$ Time, s

$\delta r$ r-direction distance between two adjacent grid points

$\delta \theta$ $\theta$- direction distance between two adjacent grid points

$\delta z$ z-direction distance between two adjacent grid points

$\Delta V$ Volume, m$^3$

mo2 position between outer cylinder surface and PCM

$B$ ‘bottom’ neighbor of grid P

$b$ control-volume face between P and B

$E$ ‘east’ neighbor of grid P

$e$ control-volume face between P and E

$i$ initial condition

$m$ mushy phase

$N$ ‘north’ neighbor of grid P

$n$ control-volume face between P and N

$P$ grid point

$s$ ‘south’ neighbor of grid P

$s$ control-volume face between P and S

$T$ ‘Top’ neighbor of grid P

$t$ control-volume face between P and T

$w$ control-volume face between P and W

i, j, k unit vector

in inlet

out outlet

s solid

1 liquid

i interface

g glycol

w wall

Greek symbols

$\rho$ Density kg/m$^3$

$\Gamma$ Diffusion coefficient, k

$\theta$ Angular-direction

$\delta$ Thickness, mm

$\mu$ Viscosity

$\eta$ Dummy variable in equation (11)

$\Delta$ Difference
Figure (7) Photographed pictures show the variation of ice melting and location of interface with time.

(a) Time = 0:30 hr.  
(b) Time = 1:30 hr.

Flow

-6.84545
-6.52727
-6.20909
-5.57273
-4.93636
-5.25455
-5.57273
-6.84545

Initial condition, Inlet flow

Flow

-6.84545
-6.52727
-6.20909
-5.57273
-4.93636
-4.61818
-5.25455
-6.20909

Initial condition, Middle flow
Figure (8) Experimental temperature (°C) distribution in ice at solidification process (initial condition) with radial direction.

Figure (9) Numerical Isothermal contours (°C) in PCM with radial direction with different time intervals.
Figure (10) Numerical enthalpy contours PCM with radial direction, with different time intervals.

(a), Initial condition, time = 0:00 min.
(b), Time = 1:00 hr.
(c), Time = 2:00 hr.
(d), Time = 3:00 hr.

Figure (11) Comparison between theoretical and experimental results of temperature distribution in radial direction.

(a), Theoretically
(b), Experimentally
(c), Theoretically
(d), Experimentally

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Figure (12) Experimental and theoretical Temperature distribution in PCM (ice-water) along cylinder at distance (12 mm) from outer cylinder surface at different time intervals.

(a) Initial condition at time = 0:00 min.  
(b) Time = 3:00 hr.

Figure (13) Variation of temperature and enthalpy of ice melting process with radial direction at different time intervals.
Figure (14) Variation of temperature and enthalpy with time at different distances from outer cylinder surface in radial direction, (a) Distance = 6 mm, (b) Distance = 12 mm and (c) Distance = 18 mm.

REFERENCES


دراسة عدديّة وتطبيقيّة لعملية التصهار النّثلج حول أنبوب اسطوانّي أفقي

جلال حمد جليل وحسن كريم عبد الله وكاظم حسين صفر

ملخص

درسنا مسألة نتلاج النّثلج الخارجي حول اسطوانة أفقيّة، في الجزء النظری، استخدمنا طريقة الحجم المحدّد لتمثيل انتقال الحرارة المتزامن لمعادلة الطاقة للشكل الأسطواني مع الإحداثيات الإسطوانيّة. استخدمنا طريقة المعاقب الخطى فوق الاترلاخ (LSOR) لحل معادلة الطاقة المتزامنة. اقترح نظام الاترلاخ لتحويل معادلة الطاقة إلى معادلة لا خطى مع الاترلاخ. في الجزء العمليّ، نبتت معدات لتخمّن قماد وذوبان النّثلج حول اسطوانة أفقيّة وقد سجلت درجات الحرارة لمادة PCM حول الأسطوانة. قوّرت النتائج العدديّة لطريقة الاترلاخ مع النتائج العمليّة وكان التوافق مقبولًا وكان الفرق بسبب إملاء الحمل الطبيعيّ في التحليل الاترلاخ.

الكلمات الدالة: نتلاج النّثلج، اسطوانة أفقيّة، طريقة الاترلاخ.