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Experimental investigation of ice melting inside cylindrical enclosure

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ABSTRACT

This paper reports experimental data inherent to the ice melting inside a cylindrical enclosure heated from the bottom making use of high technique equipment's for measuring the temperature distribution in the solid and liquid phases as well as in the melting front (moving boundary condition). Also, it was measured the reduction of pressure through this process to give more facility to measure the phase change velocity (i.e. melting rate) through the melting. Correlations for ice melting time as a function of the melt thickness, mass of melt, volume of melt, and energy of melt values. It was found the melt thickness about 5.2 cm at time of 114.5 min, and the maximum value of energy was about 578.629 kJ to melt ice mass of 1.727 kg with time of 95.5 min.

1. Introduction

The problem of ice-melting heat transfer has received much attention because they are closely human life and the development of industrial plants in cold regions. Melting phenomenon is related to a wide variety of engineering fields such as melting of ice, thawing of moist soil, latent heat of fusion, purification of metal, welding and plastics manufacturing. Melting process is classified as moving boundary problem which has been of special interest due to the inherent difficulties associated with the non-linearity of the interface conditions and the unknown location of the moving boundary. Conduction is considered as a heat transfer mode to characterize the phase change heat mechanism through this process. Kahraman et al. [1] studied numerically and experimentally melting of ice in a cubical enclosure partially heated from above. Half of the upper surface was maintained at room temperature and the other half was at 70 °C. The ice cube was maintained at its melting point at the bottom. The other side surfaces were insulated. The process was first modeled by ignoring the effect of the natural convection in the liquid phase. The resulting equations of the conservation of the energy were solved in each phase. The motion of the melting front was governed by an energy balance at the interface. This conduction model was verified by applying it to a 1-D phase change problem for which an analytical solution was available. Scanlon et al. [2] presented numerically and experimentally the process of melting a vertical cylindrical ice cube in water at different temperatures. The aim is to see the effect of the density inversion of water, which occurs approximately at 4 °C. In the experiment, the Particle Image Velocity (PIV) analysis was used to obtain the instantaneous velocity and the related properties in the fluid. A CFD investigation of natural convection ice melting has been carried out. The results show that this complex transient phenomenon can be qualified by using computational fluid dynamics and particle image velocimetry. Scalon and Stickland [3] investigated the melting of vertical ice cylinder in water. The experiments were carried out in a water-filled cylindrical Perspex barrel with adiabatic walls for Rayleigh numbers of 0.22 and 0.475×10^8. The ice crystal is suspended in the water and experimental images of the natural convection melting process were obtained using both shadowgraph and particle image velocimetry (PIV) techniques. This data is compared with numerical model which attempts to capture the melt-front on a fixed computational grid. The numerical model takes into account the density inversion effects in the water. The results show the applicability of (PIV) to this type of flow and demonstrate a simple numerical to effectively resolve the melting phenomenon. Kahraman [4] carried out numerically and experimentally two-dimensional transients melting of ice in a rectangular enclosure. Natural convection in the liquid phase due to the temperature dependency of water density is considered in the numerical model. The implicit finite difference method with fixed staggered grid approach is utilized. The simpler algorithm is formed for the solution of the pressure and velocity fields in the liquid phase. The prediction of the model is found to be satisfactory through the preliminary experimentation. Sugawara et al. [5] considered numerically and experimentally the melting of a vertical ice plate into a calcium chloride aqueous solution ($CaCl_2$-H_2O mixture) in a rectangular cavity. The ice plate melts spontaneously with decreasing the temperature at the melting front even when there is no initial temperature difference between ice and liquid. The visual observations of the liquid reveal a complicated natural convection affected by the concentration/temperature gradients which appear near the melting

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front. Melt water gradually contaminates an upper region in the initial homogeneous liquid which causes the melting rate to decrease. Aspect ratio H/W of the liquid region does not affect the melting rate within an early melting stage, however the large aspect ratio causes to decrease the melting rate during the melting process. Dorbolo et al. [6] investigated experimentally and numerically the melting of an assembly of ice block contained in a vertical cylinder and under a directional load. The total volume is occupied by the ice block and the volume of ice is simultaneously measured which allows one to determine the volume fraction of the ice in the cylinder, while the ice volume continuously decreases and sudden breakdowns of the total volume are observed. Large reorganization of the whole assembly is occurred. The maximum volume fraction is found just after a large reorganization is decreased with time. Eames and Adreft [7] connected an experimental study of the melting process for ice water containing in spherical elements. They reported quantitative data on the movement of the solid-liquid interface position with time, and the effect of sphere size on the melting process. They also reported the discharge rate and the time required to melt a spherical ice storage element.

Fukusako and Yamada [8] showed in a horizontal melt layer of ice heated from above or below, four typical situations may occur due to the peculiar characteristics of water, which exhibits a density inversion at 4 °C. When heated from above, the fluid layer consists of both a potentially stable and a potentially unstable layer if the surface temperature is higher than 4 °C, whereas the entire fluid layer is potentially unstable if the surface temperature is in the range of 0–4 °C. On the other hands, when heated from below, there will be an unstable liquid layer only when the lower boundary temperature is greater than 4 °C as shown in Fig. 1.

Huppert and Turner [9] investigated experimentally the effect of ambient stratification on the flow and transport adjacent to a vertical ice surface melting in seawater. The same problem was analytically studied by Marschall [10]. He determined experimentally the transport characteristics of a vertical flat ice slab melting in seawater. He used a schlieren system and found that the flow was upward and laminar at low ambient temperatures and that at higher ambient temperatures there was transition to turbulence. Josberger and Martin [11] carried out an excellent and extensive observation of the flow along the melting and extensive observation of the flow along the melting vertical ice surface in saline water. They found that for ambient temperatures T_∞ less than about 18 °C the flow was laminar near the ice surface and bidirectional near the bottom, while near the top of vertical ice the flow was fully upward and turbulent.

Riviere and Beer [12] reported the melting experiments of unfixed ice in an isothermally heated horizontal cylinder. The ice was heated to slightly below melting temperature. The melting experiment started by suddenly heating the tube wall to the desired temperature by heating fluid in pipe was supplied tangentially to the ice capsule from bottom and top. Photographs of the temporal ice-water interface position and of the water flow in the melted zone are presented. The flow visualization shows the influence of the density inversion of the water on the flow regimes in the melted zone and consequently on the shape of the lower ice-water interface. Melting rates correlated by use of an analytical solution are in good agreement with the experimental findings.

It can be deduced that the most of the authors investigated the experimental analysis mostly by natural and forced convection. They used air flow, different kinds of water or mixing the water with salt and

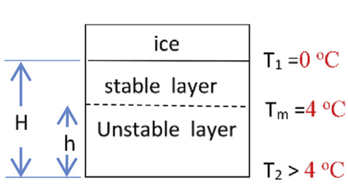

Fig. 1. Melting pattern of horizontal ice layer heated from down.

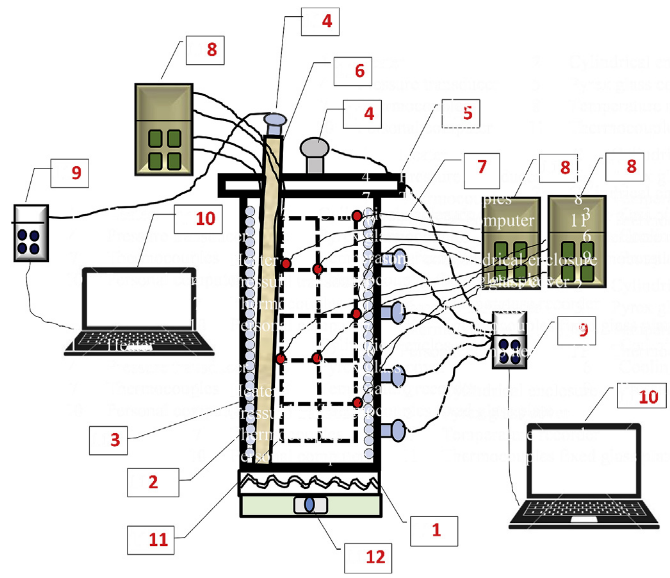

Fig. 2. Schematic diagram of rig.

another fluid to carry out the melting process. In the present research, the melting of a large ice block was heated from down with constant temperature about 100 °C. The dimensions of ice block are more closely with the dimensions of cylindrical enclosure, which was perfectly insulation for all the surroundings even the heater from down. It has been taken about 84 h to complete the melting of this ice block. The measurements of temperature distribution and profile, pressure reduction, and phase change velocity (melting rate) are taken at the first 2 h of this process. Then, the conduction mode only was used in analysis of these measurements. It was ignored the convection mode which was happened at the end time period of this process.

2. Description of experimental test rig

The rig was design and built in order to investigate the melting phenomenon for ice block of pure water inside cylindrical enclosure. Through freezing process a large mass of ice block was produced, which was estimated about 93.273 kg in a good working time was 8 h and 20 min. The dimensions of this cylindrical ice block were 40 cm diameter and 90 cm length. The schematic diagram of the rig is illustrated in Fig. 2. The main part was the cylindrical enclosure, which was designed with a wide range of domain in length and diameter, while all authors used small enclosure in different geometries. It was perfectly insulation for all the surrounding, and assumed the heat supply from the down of enclosure with a constant temperature a 100 °C as boundary condition. That means the melting process was analyzed by conduction only. This is due to the ice block was a stagnant and it was not used any assistant fluid to carry out the melting process. A two temperature recorder model BTM-42085D with 12 channels, which used to measure the temperature of 24 points inside the domain of enclosure. It has been used thermocouples type (K), and 5 pressure transducers device to measure the pressure through the melting process. Figs. 3 and 4 describe the locations of these thermocouples and pressures transducers. Cooling rate sensor was designed to measure the phase change velocity through the melting and freezing processes. It was manufactured as a copper pipe with selection dimensions depending upon the function of its work. The device dimensions are 100 cm length, 5.5 cm diameter, and 1.5 mm thickness. This pipe was welded from down and closed from the top by fixed pressure transducer sensor of 10 bars. This device was filled with pure water up to 90% of its volume. The amount of air which should be left inside the device was 10% of its volume. Then, the air was supplied to device under pressure

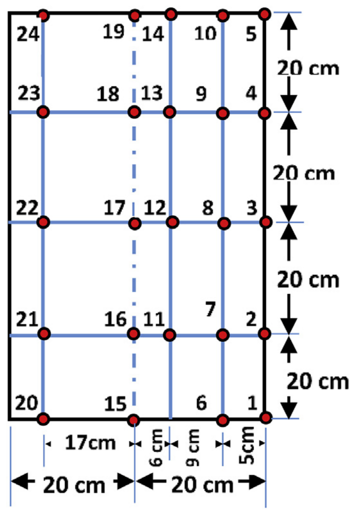

Fig. 3. Location of thermocouples inside enclosure.

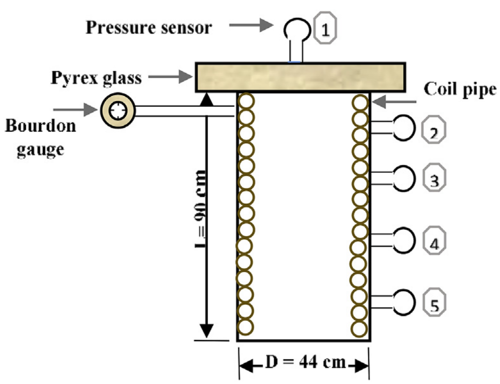

Fig. 4. Pressure sensor location on enclosure.

value between 3 and 4 bars by Bourdon gauge, which was fixed at the top wall side of device. The pressure sensor for this device also connected with the interface system. Four thermocouples type K were welded at each outside wall of this device. These thermocouples connected to another temperature recorder device in order to measure the surface temperature of cooling rate sensor through freezing and melting processes inside the cylindrical enclosure. Then, it was vertically place in the enclosure inclined from the cylinder wall toward the center of the enclosure as shown in Fig. 2. Fig. 5a and b shows respectively the schematic diagram with fixed thermocouples locations, and photograph of cooling rate sensor. The working function of this device through these two processes was detailed by Hameed [13].

2.1. Experimental procedure

1 Starting to work the electrical heater which was placed at down of enclosure. This heater also insulation and supplied with control system thermostat. Then, it has been got a constant temperature which was about 100 °C in order to start the melting process.
2 It has been mentioned that all the side, top, and down of cylindrical enclosure insulation perfectly through this process to avoid the effective from the outside boundary conditions.
3 Block of ice starting to melt, after time of interaction area which is about 4 cm far away from down. It has been found experimentally at this distance z = 4 cm, the phase change starting. That mean at this distance the solid ice reached to melting point 0 °C, and started to transform to liquid phase at different values of r-axis with different time.
4 The temperatures through the enclosure domain were measured by 24 thermocouples in different selection points. The two temperature recorder devices with SD card were recorded the temperature with time through melting process. These temperature readings were calibrated with digital thermometer, and produced correction equation.
5 It has been found the response effects pressure at the sensor which was fixed at the top cover of evaporator enclosure only, while the readings through another four sensors around the wall do not give

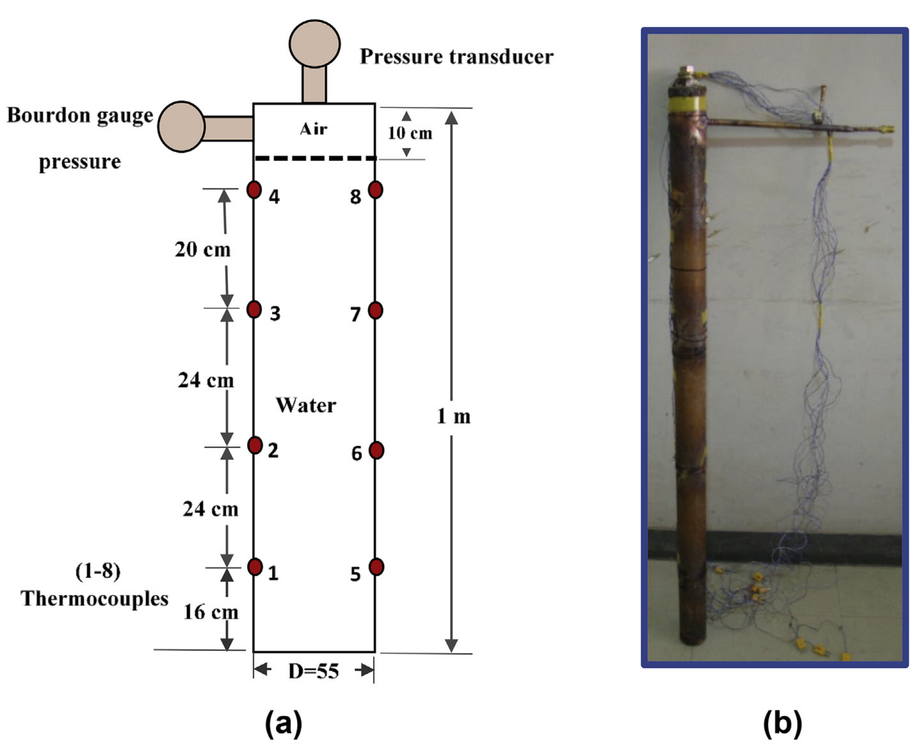

Fig. 5. (A) schematic diagram of cooling rate sensor. (b): photograph of cooling rate sensor.

reliable results. That means no variation of pressure was measured and effected through these processes. This is due to the liquid and ice block are stagnant through these processes. Only the sensor at the top cover recorded the variation of pressure due to the expanding in volume of ice through freezing, and has less density value than liquid water. While in melting the pressure values were depressed with time from high value at the end of freezing process, then these values of pressure were decreasing with time through melting process. These results were calibrated with the reading of bourdon gauge pressure and produced correction equation.

6 Cooling rate sensor working in opposite function of freezing through the melting process. This sensor starts to measure the velocity of phase change through this process. The distance of height ice decreasing with time. Then, the velocity of phase change in melting process was calculated after measured the temperature and pressure values of this device.

3. Experimental analysis

1-Melt Thickness:

The cooling rate sensor device was measured the distance of height ice melting. These values were represented the melt thickness of ice melt with time. Then, it has been estimated the volume of ice melt with time using the formula as:

$$V_{\text{ice melt}} = A \times t_m \quad (1)$$

Where

A is the area of cylindrical enclosure which was about 0.1256 m^2. Also, it was obtained the ratio V/V_o with intervals time. This ratio was called fraction of the volume of melt, V is the volume of ice melt with time, and V_o is the volume of cylindrical enclosure which was about 0.11304 m^3.

2- Mass of Melt

It was described the mass of ice melt with time from the cylindrical ice block mass, which was produced in experiment work. It has been calculated as:

$$M(t) = \rho_s \times V(t) \quad (2)$$

Where ρ_s is the density of ice which was about 916.8 kg/m^3 and V (t) is the volume of ice melt with time.

3- Energy of Melt

It can be found the energy required to melt each part of ice mass with time, which was melted from the large cylindrical ice block. This was depending upon the latent heat required to melt the ice, which was a 335 kJ/kg. The energy formula was

$$E(t) = M(t) \times L \quad (3)$$

Where E(t) is the energy variable with time, and L is the latent heat of melting. Table 1 domesticates these parameters which were analyzed experimentally with time.

3.1. Uncertainty analysis

Through experimental work the results which were measured for temperature and pressure during the melting process were corrected by function relations. These were produced from the calibration methods of these devices by comparing their readings with another's depending upon the physical phenomenon. The experimental data taken from the measurement devices have been repeated in order to have more stable and accurate readings. It has been mentioned in mathematical model of ice melt, which was presented by Hameed [13]. The convergent criteria for the numerical results of melting analysis produced more reliable solution. So, it can be used these results to estimate the percentage error of experimental results by the following equation:

Table 1
Analysis of melting parameters experimentally.

Time selected (min)	Melt thickness (cm)	Volume of melt (m^3)	V/V_o	Mass of melt (kg)	Energy of melt (kJ)
28.45	0.186	0.000233	0.00206	0.214	71.750
29.62	0.192	0.000241	0.00213	0.0069	2.314
30.18	0.206	0.000258	0.00228	0.016	5.400
31.29	0.250	0.000344	0.00277	0.050	16.973
38.6	0.329	0.000425	0.00375	0.102	34.331
55.36	0.827	0.00103	0.00911	0.561	188.247
76.96	2.3	0.0028	0.0247	1.696	568.213
95.5	3.8	0.00477	0.0421	1.727	578.629
106.4	4.9	0.00615	0.0544	1.266	424.328
114.5	5.2	0.00653	0.0577	0.345	115.725

$$error = \frac{Numerical\ results - Experimental\ results}{Experimental\ results} \times 100$$

These equations of response function gave more correction and reliability for readings result, which gave percentage of error which was about 0.1 to 0.01.

4. Results and discussion

Fig. 6 represents the temperature profile along the depth of enclosure (z-axis) at value of r = 0. It was found experimentally that the interaction distance was about 4 cm from the down of enclosure through z-axis. Also, it was deduced that at center line of the enclosure (r = 0), the time was taken a 21.1 min to reach the melting point. This is due to the center line point has low value of freezing temperature than other value of r-axis. This result was given a good agreement with experimental results of Kahraman [3]. While Fig. 7 reports the phase change temperature distribution through different radius values (phase change line) of ice block. It has been illustrated that the value of

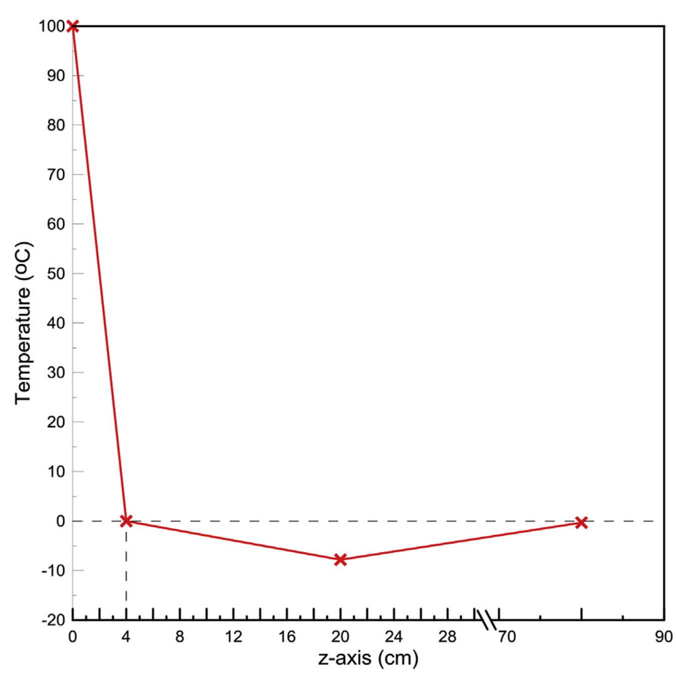

Fig. 6. Temperature profile through depth at time 21 min From the bottom to the top at center line (r = 0) of melting ice cylinder.

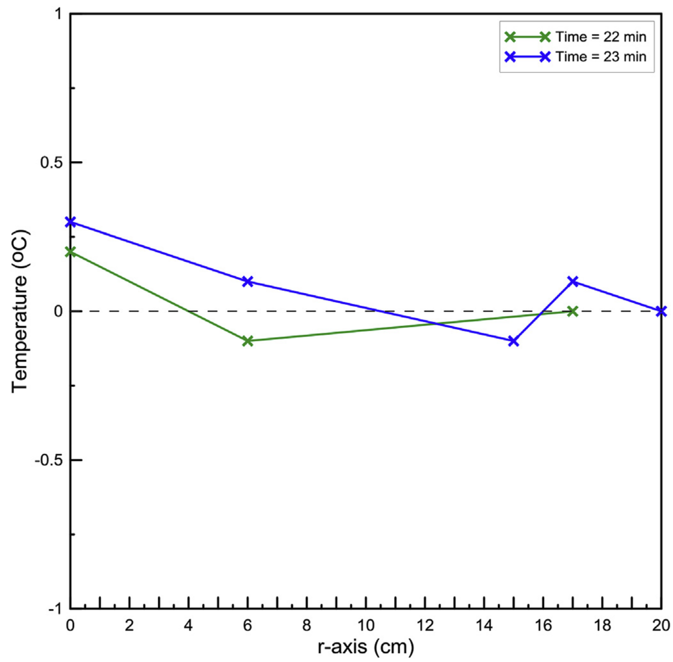

Fig. 7. Temperature distribution through phase change line with different intervals time at z = 4 cm.

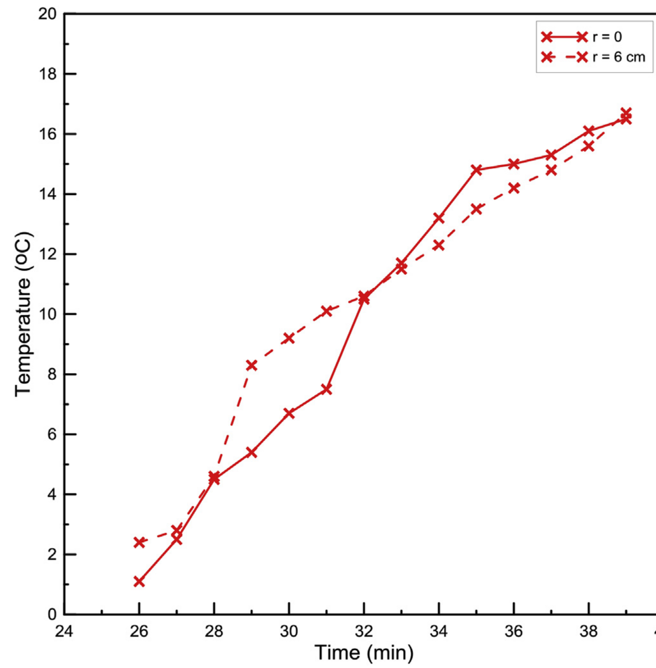

Fig. 9. Temporal variation of temperature through liquid at r = 0, and 6 cm.

temperature more closing to melting of temperature 0 °C. These temperature values were recorded between values of time 22 min–23 min. These values of time were dedicated that the phase change was happened in these five points which their location at 4 cm along the depth of ice block from down.

Fig. 8 imposes that three traces response of function to present the relationship between the temperature distribution with time for different radius values of cylindrical ice block as r = 0, r = 6 cm, and r = 17 cm respectively in solid phase. It has been observed the range of values of temperature less than the melting point 0 °C for three values of r-axis. The function relation of temperature values were increasing with time. This is due to heat supply time was not enough to start the melting temperature 0 °C at any points of width of ice block r-axis. Fig. 9 dominates the temporal relation of temperatures distribution through different values of width with range levels of time higher than the happening time of phase change. These experimental results were dedicated the melting process starting, and the temperature increasing than the melting point with levels of time higher than 24 min. The traces response functions of these results give similar relation. It can be seen that the melting rate is a linear function of time in different values for width point as r = 0, 6, 15, and 20 cm. Fig. 10 shows the temperature distribution through the width of cylinder ice block (r-axis) with different levels of time. These results obtained from experimental work for melting process, which was measured in time when the bottom

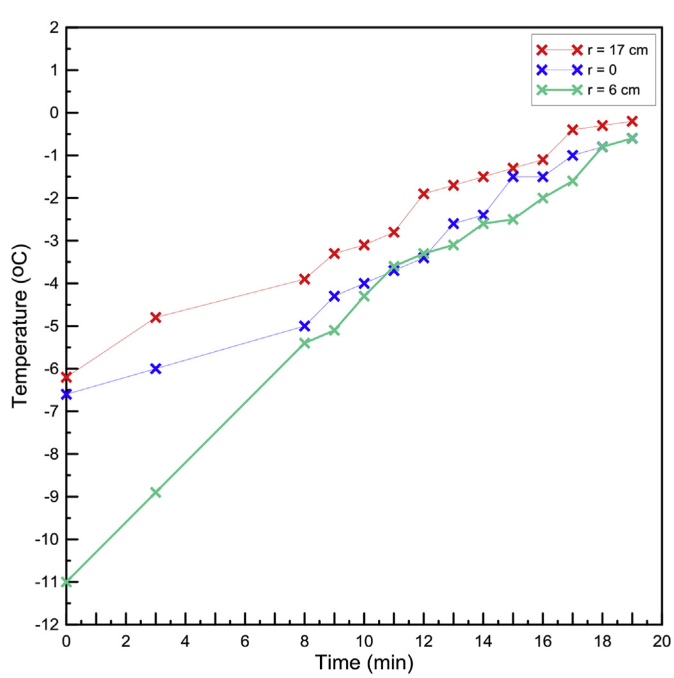

Fig. 8. Temporal variation of temperature through solid phase.

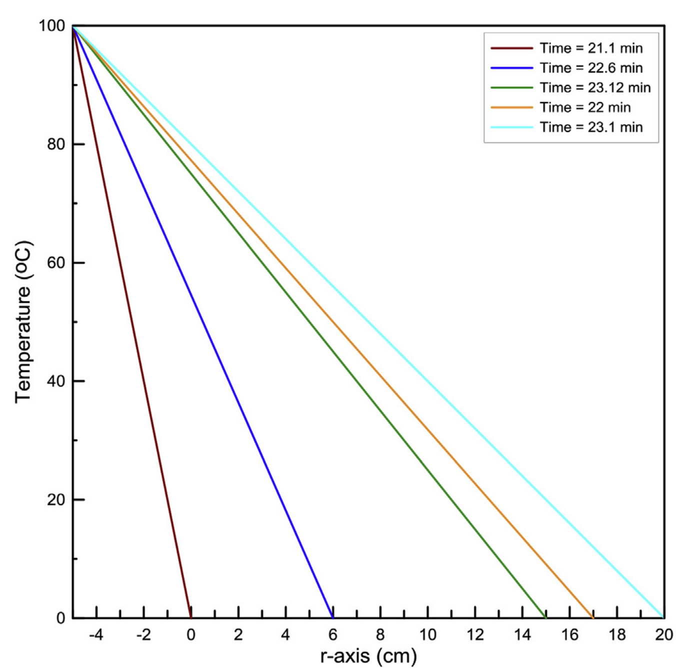

Fig. 10. Temperature profiles obtained from experimental work for melting of ice subjected to 100 °C, at z = 4 cm.

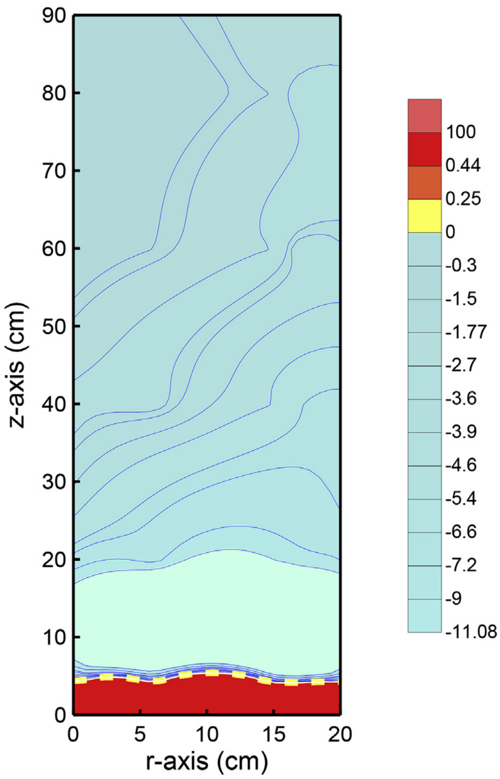

Fig. 11. Isothermal contour map of temperature distribution through cylinder for melting process at time = 23.1 min.

layer of ice block starts to melt i.e. to reach the melting point 0 °C. The results were observed that all the points were chosen in enclosure width in solid phase are maintained at the melting temperature 0 °C. These were took different time levels to reach this temperature 0 °C as pointed in this figure for the five values of width. The measuring time levels of these points to reach the melting temperature are between 21.1 min for the center point to 23.1 min for the far away point near the wall of cylinder. These different values in time levels were due to these points have different values of freezing temperature before melting. Also, this figure indicates that the melting starts at distance of depth (z-axis) as 4 cm far away from the bottom of enclosure, when a boundary condition with maintained temperature 100 °C was placed. This distance was called interaction distance before the melting process starts at it with suitable time it was measured and proved by the present experimental work. This distance location was predicted through the numerical model which was designed through the work of Hameed [13]. These results were coincided with theoretical results of Gau and Viskanta [14].

Fig. 11 moderates the isothermal contour map of temperature distribution in cylindrical ice block for melting process during 23.1 min. At this time the phase change phenomenon happened i.e the ice tarts to melt at melting temperature of water 0 °C. This figure gives more reliable description of the melting process mechanism. It has been shown that the bottom surface plane represents the interaction area, which was about 4 cm from the down. At this line the distance of the ice starts to melt at 0 °C and around it. The upper parts represented the solid phase for the melting process. This is due to the unique properties of ice water than others materials, that more detailed by Desouza and Vielm [15].

Fig. 12 devotes the pressure values which were recorded from pressure transducer sensor which was fixed in the top of cover. Only the pressure transducer sensor in the top of cover was measured the system at high pressure value of freezing process due to the ice expanding through freezing and has high pressure value as 8.6 bar at the end of freezing process. From this pressure value the heat mechanism of melting process starting as initial condition. The trace function response was depressed with time of melting from high value to lower value as 1.3 bar at the time of 450 min. This is not the end time of melting process. This process took a long time to complete the melting process of a large mass of ice block which was about 93.271 kg. It has been taken about 84 h to complete the melting of this mass. It should be mentioned that the pressure after 450 min remains as a constant, which was very little reduction observed. The response function of the pressure values through the melting process was deduced as exponential function.

Fig. 13 dedicates the relation between the distances of melting with time i.e. the melt thickness. This was represented the melting rate

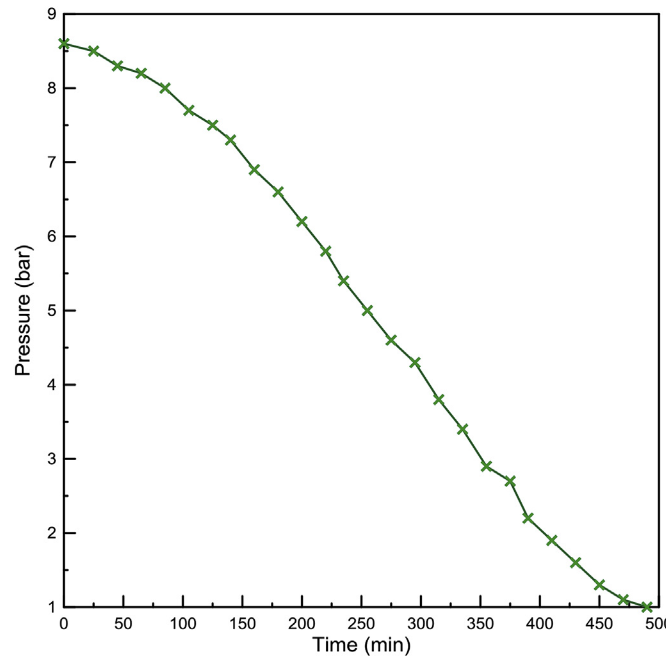

Fig. 12. Variation of pressure with time through melting process.

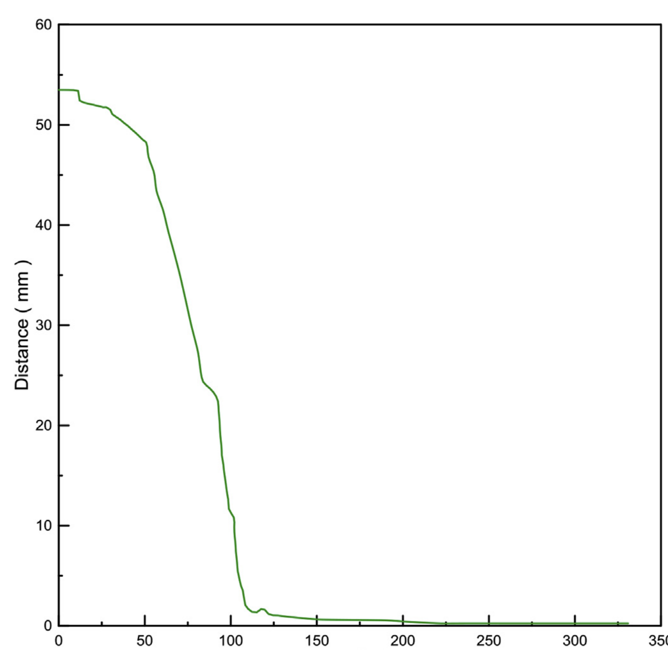

Fig. 13. Variation distance of melting with time.

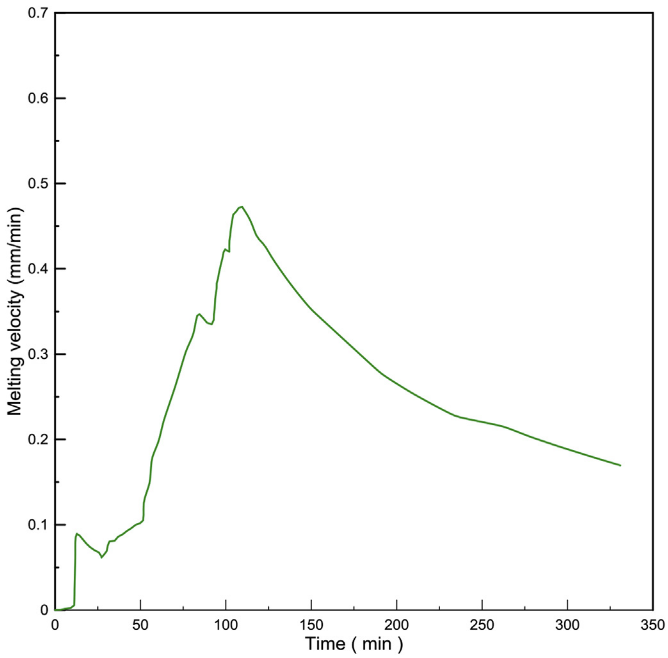

Fig. 14. Variation of melting velocity with time.

which was measured by cooling rate device. The trace response function was depressed from high value of 5.4 cm–0.18 cm at time of 108 min. Then, very low reduction observed until time of 330 min as it was posed in reduction. This is due to the melting velocity starts in reduction at this time, and also the energy supply becomes far away from the ice surface. Because the unique properties of ice than other materials the ice was floated over the melting liquid due to the liquid density was higher than solid ice. Fukusako and Yamada [8] demonstrate that when ice heated from down, there will be unstable liquid layer, when the lower boundary temperature is greater than 4 °C as shown in Fig. 1. In the present work the ice was heated from down with 100 °C as one boundary condition was supplied. Fig. 14 deduces the velocity profile of phase change with time depending upon the range values of melt thickness and melting time. The response function starting from zero then starts increasing until maximum value at 0.474 mm/min at time of 108.9 min. The reduction of response was observed as in negative exponential until 330 min. These values of velocity were devoted as melting rate of ice through melting process, which were recorded by cooling rate sensor.

Fig. 15 dominates the melt thickness verse time through the experimental work of melting process. It has been seen that the trace function response of melt thickness was increased with increasing the time, and the function response as a polynomial function. The maximum value of melt thickness was obtained as 5.2 cm with time of 114.5 min This result agree with theoretical result of Kahraman et al. [1]. Fig. 16 indicates the mass of melt value of ice which was melted from the large ice block mass. It was about 93.271 kg which was produced through solidification process. The trace response function was starting from the value of mass at time of 28.45 min reduction to lower value as pointed with time. Then, the mass of ice melt value began to increase as time increasing until maximum value of mass as 1.727 kg at time of 95.5 min. The response function starts in reduction again after the maximum value, which was reached as 0.345 kg at time of 114.5 min. The summation of these masses value through the levels of time from 28.45 to 114.5 min was represented the total mass of ice which was melted from the original mass of ice block with value of 93.271 kg. This result was consistent with result of Arid et al. [16].

Fig. 17 describes the relationship of function response of energy required to each value of melt thickness was melted with time from the large ice block. This trace function response was obtained from experimental work for measuring the melt thickness value by cooling rate device with energy. This energy was calculated depending upon the each mass part of ice melt, and the latent heat value of ice melting. This function starting with value of energy was about 71.750 kJ at very low value of melt thickness, and reduced to value of 0.0069 kJ. Then, starts from time of 30.18 min to increase until maximum value of 578.629 kJ at time of 95.5 min, and melt thickness value of 3.8 cm. It has been observed to reduce again to value of 115.725 kJ at time of 114.5 min with melt thickness value was about 5.2 cm.

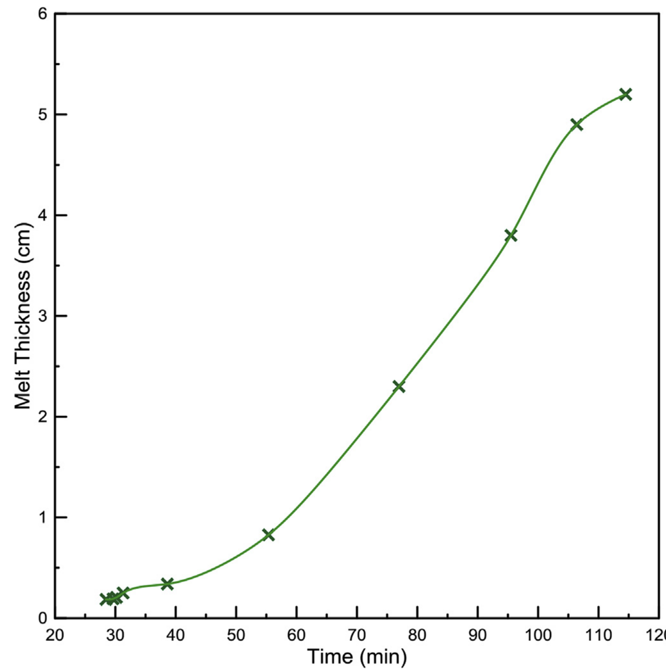

Fig. 15. Melt thickness verse time plot obtained from the experimental work along r-axis.

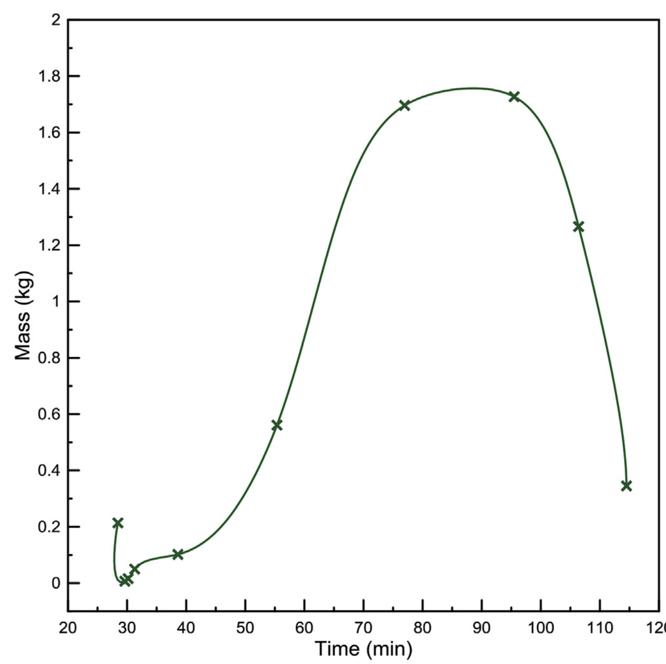

Fig. 16. Variation of mass with time through melting process.

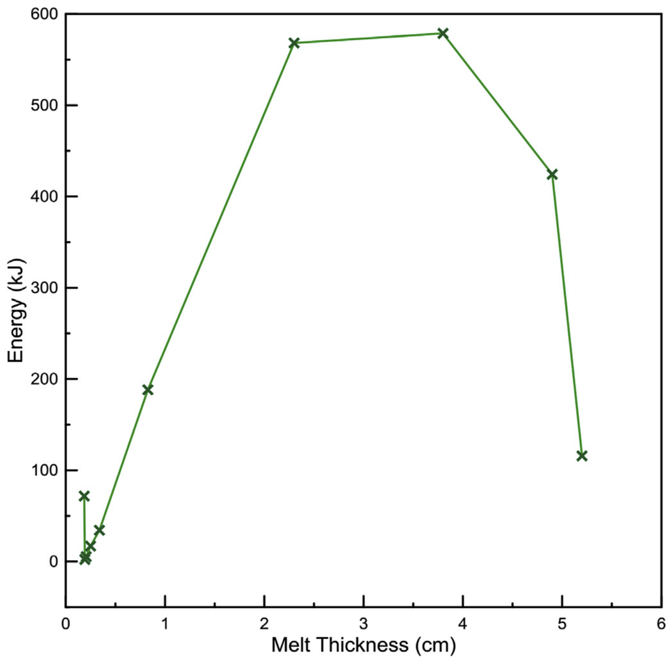

Fig. 17. Variation of energy with melt thickness of ice through melting of ice block.

5. Conclusions

The present work investigates the mechanism of melting process for ice block. The main conclusions are drawn as follows:

1 The distance of interaction (interface line) was about 4 cm from the heat supply with phase change occurring in the range 20–23.1 min.
2 The velocity of phase-change was measured by cooling rate sensor device. These values gave a dramatic of response function during the melting process. The velocity profile was pointed out a maximum value about 0.474 mm/min at time of 108.9 min and reduced to 0.198 mm/min at time 330 min.
3 The pressure values through the melting process were started from a maximum value 8.6 bar as an initial value and depressing with time to 1.3 bar at the time of 450 min.
4 The experiment results of temperatures distribution and profile for melting process was given more reliable result and was coincided with theoretical of Hameed [13].
5 It was found that energy value to melt each part of ice mass with time. The maximum value of energy was about 578.629 kJ to melt ice mass of 1.727 kg with time of 95.5 min. However the minimum value was about 2.314 kJ to melt ice mass of 0.0069 kg with time of 29.62 min.
6 It was taken 8 h to melt about 6 cm from the thickness of ice block. That means it has been taken a long time to complete the melting of a large mass of ice block.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijthermalsci.2018.11.024.

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