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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF TEMPERATURE DISTRIBUTION FOR MEAT DURING FREEZING PROCESS

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ABSTRACT

The prediction of freezing meat inside the cold storage is studied experimentally and numerically using CFX14.5. In the present work a prototype cold storage for meat has been designed and constructed with dimensions 1 m in length x 1 m in width x 1 m in height. Temperature distributions of regular shape of meats were determined for storage temperature -21°C inside the cold storage, where each part of meat is located in one of the three levels (bottom, medium and top) inside the cold store. The air velocity distribution has been measured by using metal vane anemometer in the directions of (x, -x, y, -y, z and -z) around the meat and the results have been used in the numerical simulations. In the numerical simulations the temperature distributions are based on transient, Navier-Stokes equations, turbulence is taken into account using a standard κ–ε model for air flow and assumed as steady turbulent state, meats are presented as solid domain with variable thermophysical properties as function of temperature and mass and heat transfer due to evaporation are regulated due to including product casings. During the freezing the properties of meat change during the three stages each stage having specific properties. The minimum temperature of the product was located in the top level and very close to their surrounding storage air temperature both due to exposure to higher air velocity from the fans. The total error of compression between the experimental and numerical temperature distributions of meats is equal to 18.7%.

Key words: Cold Store; CFD Model; Simulation; Air Flow; Temperature Distribution; Meat; Thermo-Phyical Properties; Food Industry.

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NOMENCLATURE

Symbol	Description	Unit
C_1, C_2, C_μ	Constant Coefficient in k- ε Model	
C_i	Food component specific heat	(kJ/kg.K)
C_{pu}	Specific heat at above freezing (before freezing)	(kJ/kg.K)
C_{pf}	Specific heat at below freezing (after freezing)	(kJ/kg.K)
C_v	Volumetric loading rate	kg/m^3
D_h	Hydraulic diameter	M
H_f	enthalpy of food at initial freezing temperature	kJ/kg
h_{if}	The product latent heat	(kJ/kg)
I	Turbulent intensity	
k	Thermal conductivity	W/m.K
L_o	latent heat of fusion	kJ/kg
P	Preesure	N/m^2
P’	modified pressure	N/m^2
t	Time	S
$T_{initial}$	Initial temperature of product that entering the storage	K
T_{final}	Final temperature of product	K
$T_{freezing}$	initial freezing point of product	K
T_o	freezing point of water	K
T_r	reference temperature (zero enthalpy)	K
U	Velocity vector	(m/s)
u,v,w	Velocity components of X,Y & Z directions	m/s
x_b	Mass fraction of bound water	
x_i	Mass fraction of the food component	
x_{ice}	Mass fraction of ice	
x_p	Mass fraction of protein	
x_s	Mass fraction of solids	
x_{wo}	Mass fraction of water in unfrozen food	
x_i^v	Volume fraction of constituent	
Greek symbols		
α	Thermal Diffusivity	m^2/s
ε	Turbulent Energy Dissipation Rate	m^2/s^3
κ	Turbulence kinetic energy	m^2/s^2
Φ	Dissipation function	
ρ	Density	kg/m^3

Symbol	Description	Unit
ρ_i	density of the food constituents	kg/m^3
μ	Dynamic Viscosity	N.s/m^2
μ_{eff}	Effective viscosity	(kg/m.s)
μ_T	Turbulent viscosity	(kg/m.s)
λ	second viscosity	(kg/ms)
$\sigma_k, \sigma_\varepsilon$	Empirical Constant	

1. INTRODUCTION

Food freezing, which is a process used to minimize physical, biochemical and microbiological changes in food, is of great importance in the food industry. This preservative effect is maintained by subsequent storage of the frozen food at a sufficiently cold temperature. The freezing process for foods with high water content, between 50% and 95%, is divided into three stages; the first is precooling stage. This involves cooling down from the initial temperature of the product to the product without effecting phase change, and is referred to as sensible heat. The second is phase change stage; this stage covers the formation of ice in the products and extends from the initial freezing point to a medium temperature about 5°C colder at the center of the product. The third is tempering stage; this is a cooling-down period to the ultimate temperature for storage and begins when the contribution of the latent heat is negligible compared to that of the sensible heat. The frozen product has a non-uniform temperature distribution: warmer in the center and coldest at the surfaces. Its average temperature corresponds to the value reached when the temperature of the product is allowed to equilibrate. In general, it is recommended that the product be cooled in the freezer to an equilibrium temperature of -18°C or colder [1].

There are several studies on the experimental and numerical investigation of temperature distribution in food industry:

Pierre Sylvain Mirade et al. 2002, [2], studied three dimensional CFD calculations for designing large food chillers. The CFD code Fluent/UNS was used to simulate the airflow patterns inside the chiller. This procedure was applied to a pork chiller containing 290 carcasses. Two design cases differing in inlet air direction and flow rate, and two functioning modes, batch and continuous were analyzed. Experimentally the carcasses arranged in in six rows (47 in rows 1 and 6, and 49 in the other rows). For the continuous chiller analysis the mean, center and surface temperature kinetics calculated for a carcass weight of 80 kg, where the average velocity is 0.17 m/s, Surface temperature is always about 15 °C lower than the mean temperature and storage temperature -10°C. Numerical result were made to determine the air velocity and air temperature inside a batch chiller the results show the average is 0.2m/sec and 0°C respectively. the results show that a further 8 hr are needed to reach a mean temperature of 7°C at the core and the total chilling time of 13hr changing from first ventilation level to the second reduces the chilling time by only 20 min, while increasing the total weight loss from 1.3 to 1.7%. **Jihan, 2010, [3]** Studied the heat transfer during cooling for irregular shaped meat and poultry products. Numerically a three-dimensional finite element algorithm implemented in Java was used to solve the model. Model validation was conducted using data collected in four different meat processing facilities, under real time varying processing conditions. The model was adapted to receive input parameters that are readily available and can easily be provided by meat processors such as air relative humidity, air temperature, air velocity, type of casing, duration of water shower, and product weight and core temperature prior to entering the chiller. **Gong Jianying et al. 2010, [4]** a three dimensional mathematical model is established to study the flow field distribution and radish temperature distribution inside a cold store. The result shows the flow field is very non-uniform distribution is harmful to cold storage effect and the storage product. **Seyed Majid et al. 20012, [5]** presented a numerical model to predict air flow, heat and mass transfer in order to evaluate the cooling performance of a typical full loaded cold storage using CFD code fluent 6.1. Apples are packed in the vented containers of 30 kg weight. The results showed the temperature difference between 5.5°C and 9.5°C between the hottest and coolest product's temperature during the cooling time. Also, the results shows the errors of about 23.2% between the experimental and numerical, and 9.1% were achieved for velocity magnitude prediction in the cool storage and the product weight loss after 54 days of cooling in the loaded cool storage, respectively. The objectives of the present paper are to investigate experimentally and numerically temperature distribution of meats that distributed in three levels inside the cold store during freezing process for air storage temperature below -20°C.

2. MATHEMATICAL MODELING

2.1. Physical model and thermo-physical properties of meat:

The dimensions of the simulated meat are (18cm × 11cm × 3cm) distributed in three levels inside the cold storage. Type of meat used in the present work are Indian cut meat with the moisture content and its composition (see table (1)) are taken from Babji, 1989 **[6]**. The thermo- physical properties (such as thermal conductivity, specific heat, enthalpy and density) of meat are calculated from empirical relations ASHRAE, 1998, **[7]**. The essential equations for thermo- physical properties of meat as the following:

$$x_{ice} = (x_{wo} - x_b)\left[1 - \frac{T_f}{T_{initial}}\right] \tag{1}$$

$$x_b = 0.4x_p \tag{2}$$

$$\rho = \frac{1}{\sum x_i / \rho_i} \tag{3}$$

$$c_p = \sum c_i \; x_i \tag{4}$$

$$H = H_f + (T_{initial} - T_{freezing})(4.19 - 2.3x_s - 0.628x_s^3) \qquad (for\, unfrozen\, meat) \tag{5}$$

$$H = (T_{initial} - T_r)[1.55 + 1.26x_s - \frac{(x_{wo} - x_b)L_{\circ}T_{freezing}}{T_r T_{initial}}] \qquad (for\ frozen\, meat) \tag{6}$$

$$k = \sum x_i^v \; k_i \tag{7}$$

$$x_i^v = \frac{x_i / \rho_i}{\sum (x_i / \rho_i)} \tag{8}$$

Table 1 Thermal property models for unfrozen composition data, initial freezing point [6].

Food Item	*Moisture Content,%* x_{wo}	*Protein %* x_p	*Fat, %* x_f	*Carbohydrate, %* x_c	*Fiber, %* x_f	*Ash, %* x_a	*Specific heat above freezing kJ/kg.K*	*Specific heat below freezing kJ/kg.K*	*Initial freezing point, ºC*
Indian meat	*76.3*	*20*	*1.4*	*0.0*	*0.0*	*0.83*	-	-	*-1.1*

2.2. Numerical model

To simplify the mathematical model, a number of assumptions are assumed, transient condition as analysis type, total time (80000 second) and times steps (10 second) for meat distributed in three level top, medium and bottom; Three dimensional, Turbulence medium intensity equal (5%), thermo-physical properties of meat are variable with temperature of meat, The air flow around the meat is assumed as steady turbulent state and the meat is represented as solid materials. The air velocities around the meat are measured experimentally by using the metal vane anemometer and the results are used in the numerical simulation.

According to the above assumption, the following equations for air and meat are given [8, 9]:

Continuity $$\frac{\partial \rho}{\partial t} + \rho\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right] = 0 \tag{9}$$

Momentum $$\rho\left[\frac{\partial U_i}{\partial t}\right] + \frac{\partial}{\partial x_j}\left(U_i U_j\right) = -\frac{\partial p'}{\partial x_i} + \mu_{eff}\nabla^2 U_i \tag{10}$$

Energy $$\frac{\partial(\rho T)}{\partial t} + div(\rho T U) = -p\, div(U) + div(k\, grad T) + \Phi \qquad (for\ fluid\ domain) \tag{11}$$

Equations of state $$\frac{\partial(\rho T)}{\partial t} = div(k\, grad T) \qquad (for\ solid\ domain) \tag{12}$$

$$\Phi = \mu\left\{ 2\left[(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2 + (\frac{\partial w}{\partial z})^2\right] + (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})^2 + (\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x})^2 + (\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y})^2 \right\} + \lambda(div U)^2 \tag{13}$$

$$\mu_T = C_\mu \rho \frac{\kappa^2}{\varepsilon} \tag{14}$$

$$\frac{\partial \rho\kappa}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j \kappa) - \frac{\partial}{\partial x_j}\left[\frac{\mu_T}{\sigma_\kappa}\frac{\partial \kappa}{\partial x_j}\right] = \mu_T \frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \rho\varepsilon \tag{15}$$

$$\frac{\partial \rho\varepsilon}{\partial t} + \frac{\partial}{\partial x_j}(\rho U_j \varepsilon) - \frac{\partial}{\partial x_j}\left[\frac{\mu_T}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] = C_{1\mu}\frac{\varepsilon}{\kappa}\frac{\partial U_i}{\partial x_j}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - C_{2\mu}\frac{\varepsilon^2}{\kappa}\rho \tag{16}$$

$$k = \frac{3}{2}(U \times I)^2 \quad , \quad \varepsilon = \frac{k^{3/2}}{0.3 \times D_h} \tag{17}$$

$$C_\mu = 0.09\,;\ C_{1\mu} = 1.44\,;\ C_{2\mu} = 1.92\,;\ \sigma_\kappa = 1.0\,;\ \sigma_\varepsilon = 1.3 \tag{18}$$

2.3. Initial boundary condition

The initialization of the model is important for convergence. If the initial conditions are poor, then it takes longer to converge or it may even result in divergence. In the present work the initial conditions are:

1. The initial temperature of meats located at top, medium and bottom levels are 32 ºC, 31 ºC and 30 ºC respectively.
2. The initial condition of air domain at the surrounding of the meat with initial temperature -21.5 º C, the Cartesian velocity components (U=0, V=0 and W=0) in m/s and relative pressure (0) in Pa.

2.4. Boundary condition

Air velocity and temperature open boundary condition are selected for the air surrounding the meat with velocity type Cartesian with insert option automatic with value for each side of air depends upon the experimental velocity measurement around the meat that located on the top, medium and bottom levels inside the cold store. These open velocity are occur in the dimensions (-X, X, -Y, Y, -Z, Z) are (-1.21, 1.47, -1.12, 0, 0, 0) m/sec on top level, (-0.22, 0.22, -0.1, 0, -0.6, 0) on medium level and (-0.7, 0.2, -0.1, 0, -0.53, 0.58) on the bottom level respectively. Insert the open temperature -21.5 ºC for all this six side. Wall boundary condition is selected for the solid meat domain with outside temperature (-21.5 ºC). Interfaces boundary condition types (fluid solid) are selected. A tetrahedral mesh was generated using (43970) elements and (9820) nod.

3. EXPERIMENTAL WORK

Cold storage has been designed and constructed depends on the provided materials and equipment to achieve the freezing temperature below -20ºC. The outside and inside volumes of the cold store are 1m3 and $0.512m^3$, respectively, as shown in figure (1-a). Hermetic sealed compressors and air cooled condenser was located at the outside of the cold store. Force convection evaporator is fixed at the ceiling of the cold storage as shown in figure (1-b), this unit has two fans and the air velocity for each fan is 3.2m/s.

Meat temperature distribution have been measured and recorded data in three parts of meat block, where each part is located in one of the three levels and has nine thermocouples, with 2.25 cm separated distance between each thermocouple, as shown in figure (2). The data are saved in SD card for the three 12 channel data logger that used in the present work. The Air velocity has been measured by using the metal vane anemometer, that connected to the 2D holder, inside loaded cold store with 5.4kg of meat, as shown in figure (3), and for dimensions (x,-x, y, -y, z and -z).

(a) (b)

Figure 1 (a) The cold storage and (b) The evaporator and fans (inside unit).

Figure 2 Thermocouples distribution to measure meat temperature at three levels

Figure 3 Measurement of air velocity around the meat using metal vane anemometer.

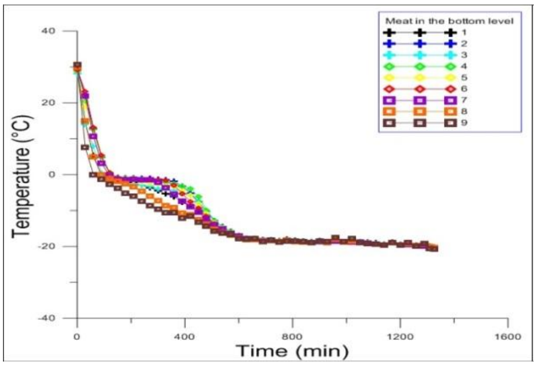
4. RESULTS AND DISCUSSION

4.1. Experimental results

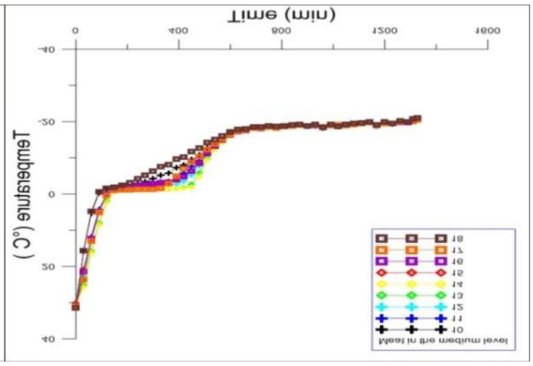
Temperature distribution inside meat has been measured along the z-direction, where the distance between one of the thermocouple and another is 2.25 cm. The initial temperatures of the meat at the top, medium and bottom levels were 32°C, 31°C and 30°C respectively. Since meat is frozen from the outside and then toward the center, it is impossible to judge by the outward appearance or the feel of the meat whether the whole of it is frozen. The surface of the meat, which is close to the freezing medium, will very quickly be reduced to a temperature near that of the freezer. The temperature inside the meat will, however, change more slowly. Since the freezing time of a product is taken for the warmest point of the meat to reach a desired temperature, it is essential that temperature measurements can be taken at the points which are likely to be frozen at last as shown in Figure (4), where the apparent freezing time to -21°C can vary from more than 22 hours and depends on where the temperature of the meat is measured.

4.2. Numerical results

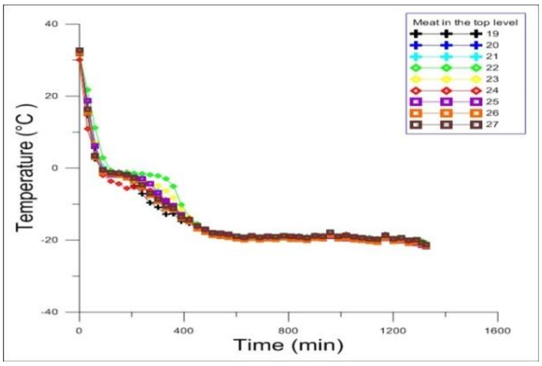
At the beginning, the initial temperature of the meat located on the top, medium and bottom was 32°C, 31°C and 30°C and by using the initial properties for meat at this temperature until the meat reach -1°C this precooling stage. From -1°C to -3°C this phase change stage has meat properties at temperature -3°C (this is the final degree for phase change stage that has been chosen its properties for meat at this stage) and this stage are very slow. And from -4°C to -21°C these contain both two degree of fast phase change stage and the other are sub-cooling stage, they have the properties of meat at temperature – 21°C. In addition the behaviors of the temperature distributions, as a function of time, are located along the meat with same distance between each point as shown in figure (5). Temperature distributions located on the center of XY-plane with time (240 min, 960 and 1326 min) as shown in figures (6,7 and 8).



(a) Bottom level

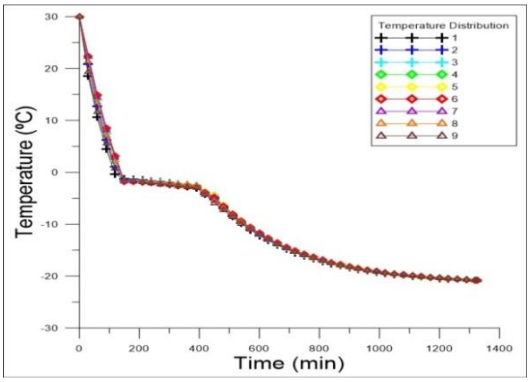


(b) Medium level

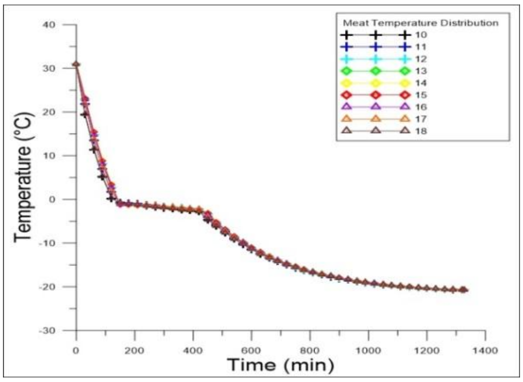


(c) Top level

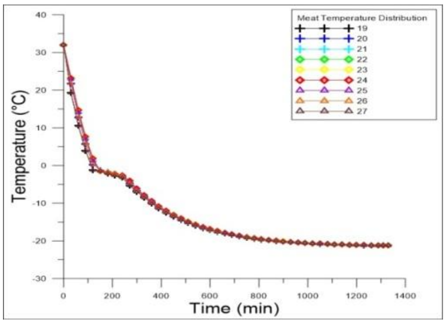
Figure 4 Temperature distribution inside the meat for storage temperature -21°C.



(a) Bottom level

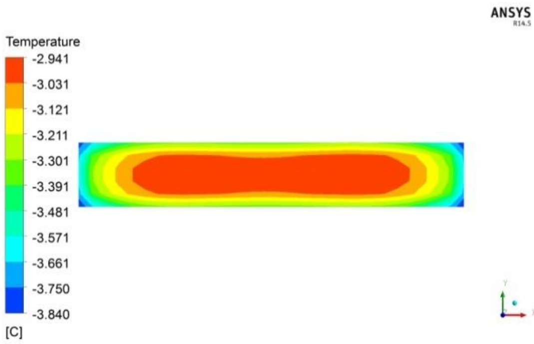


(b) Medium level

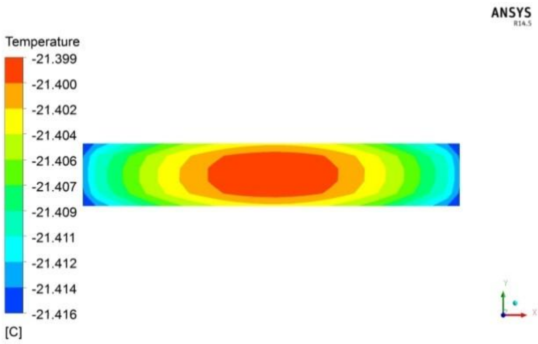


(c) Top level

Figure 5 Temperature Distribution inside the meat as function of time.

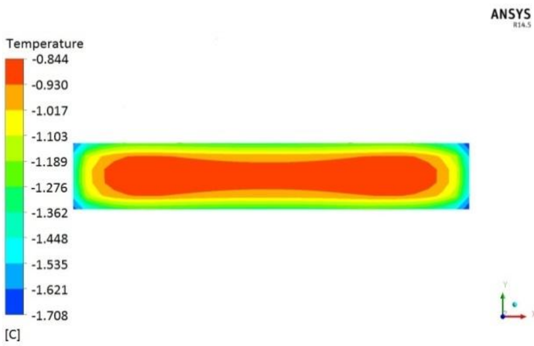


(a) 4 hours (240 minute)

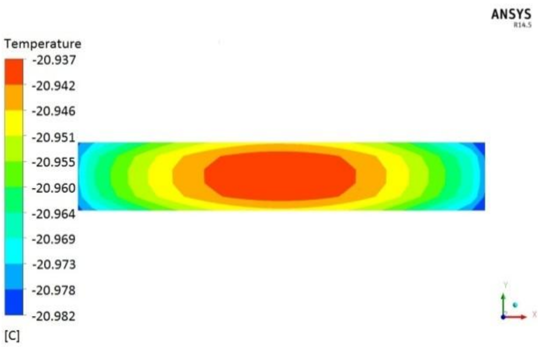


(b) 21.1 hours (1326 minute)

Figure 6 Temperature distribution of meat along XY-plane for the meat located on the top level.

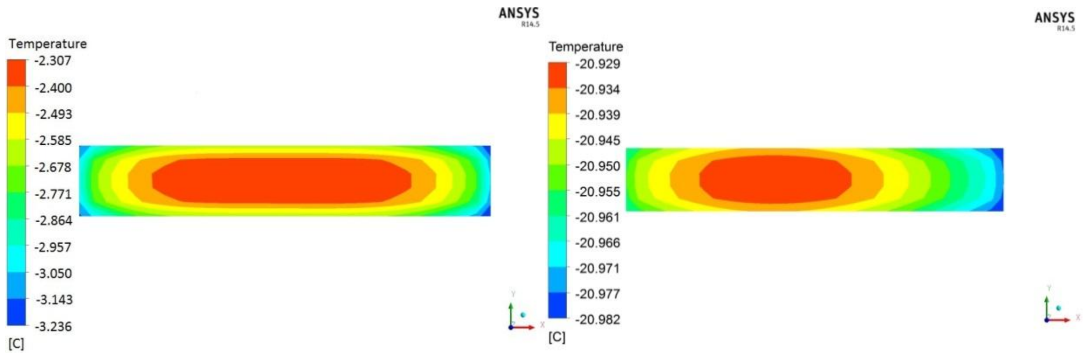


(a) 4 hours (240 minute)



(b) 21.1 hours (1326 minute)

Figure 7 Temperature distribution of meat along XY-plane for the meat located on the medium level.

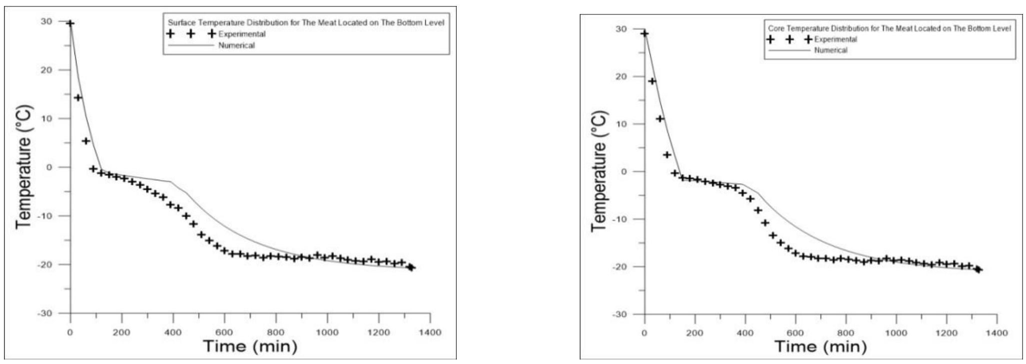


(a) 4 hours (240 minute) **(b)** 21.1 hours (1326 minute)

Figure 8 Temperature distribution of meat along XY-plane for the meat located on the bottom level.

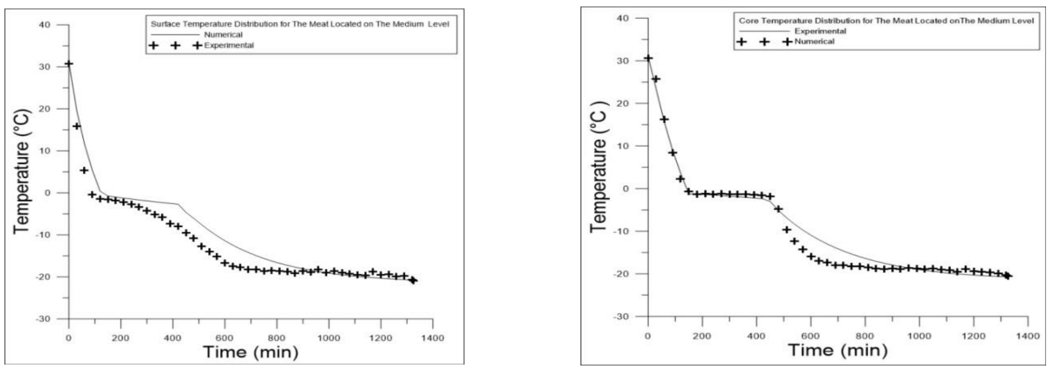
4.3. Comparison between experimental and numerical results

product core and surface temperature results located in the three levels (bottom, medium and top) inside the cold store also been comparison between the experimental and numerical results as shown in figures (9, 10 and 11) respectively, so the total error of comparison between the experimental and numerical of meat temperature distribution equal to 18.7%. Temperatures distributions along the meat length with distance 2.25cm from point to point after 1326 minute (22.1 hours) experimentally and numerically for the bottom, medium and top levels as shown in figure (12).



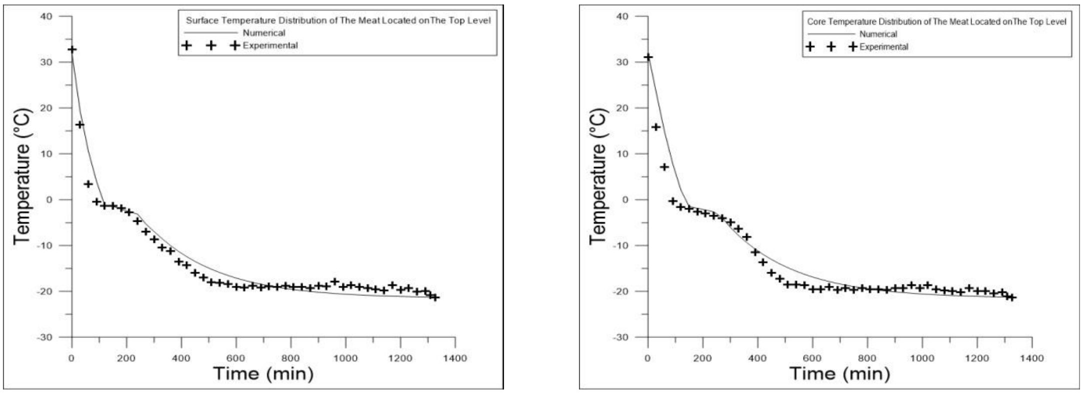
(i) Surface (ii) Core

Figure 9 Temperature distribution at the surface and core of meat located on the bottom level.



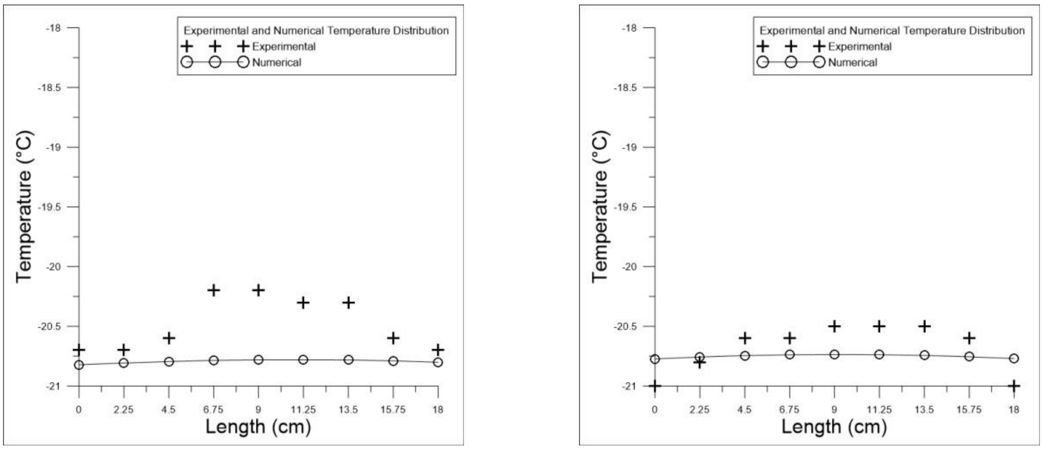
(i) Surface (ii) Core

Figure 10 Temperature distribution at the surface and core of meat located on the medium level.

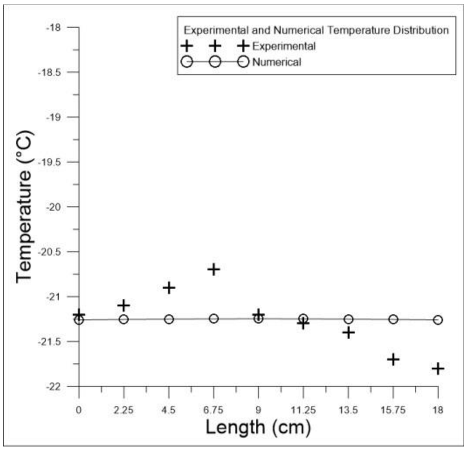


(i) Surface (ii) Core

Figure 11 Temperature distribution of the surface and core of meat located on the top level.



(i) Bottom level (ii) Medium level



(iii) Top level

Figure 12 Comparison between experimental and numerical for meat temperature distribution with length after 1326 minute for meat located at three levels.

5. CONCLUSIONS

From the present work results for the temperature distribution of meat inside the cold store, different distinguish conclusions have been pointed out:

1. The product temperature is found strongly storage air temperature dependence. This indicates that the distribution of temperature and other dependent parameters could be different if the conditions of air flow are changed as an input in the model.
2. The minimum temperature of the product at the top level in a cold storage is due to the higher air velocity exposure.
3. It is concluded that in the case where the storage temperature could not be brought down to a desired storage temperature within the stipulated time, the locations of higher product temperature will caused a maximum deterioration of the product.
4. Most of pervious research is used constant thermo physical properties; this is wrong because during the freezing the properties of meat change during the three stages each stage having specific properties.

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