A Simulation Practices of Investigation Based on Keys Parameters by Affecting the Process of Freezing Molten Steel in Casting Molten

*** Corresponding author: *Adel Khalleefah Hamad Darmeesh**
Head of the Department of Engineering Sciences
College of Engineering,
Faculty Member at Department of Materials and Minerals Engineering,
Ajdabiya University

Abstract
The alloying elements are added to pure molten for the purpose of improving the mechanical properties, and then pouring the molten in the casting machines to put it in the form required for its manufacture. The casting systems are different in their specifications, which include billets and slabs. This study focuses on casting the molten in the system of casting the veins. After casting the molten, it is subjected to various rolling processes and thermal and chemical treatments to put it in the final state of sale or use for the purposes for which it is manufactured.[6] The simulation aims to use the mathematical method to study the thickness sensitivity of the frozen layer of molten steel in casting molds to some of the parameters affecting it as these parameters change in a given range.[9] If this research can determine the temperature of each cell or node within the molten steel during the cooling period this research can obtain the thickness of the frozen layer of molten steel, and also this research can know the microscopic structure of frozen molten steel during cooling.

Keywords: *Freezing Molten Steel, Casting Molds, thermal conductivity, copper mold, frozen molten thickness, COMSOL software.*

1. Introduction

Iron is one of the earliest discovered minerals and is symbolized by the symbol Fe and its atomic number 26 Iron is placed in the periodic table in Group VIII and the fourth cycle, and iron is the fourth largest in terms of availability in nature. Iron is found in nature in the form of chemical compounds, the most common iron oxides. There are two basic ways of iron ore and mining and converting them into different types of steel. The first method is known as integrated iron and steel, where this method begins with open mining or underground mining of iron ore rich in minerals. After extraction of raw iron blocks, they are broken down into pieces so that they can be easily added to the smelting furnaces, through which the iron ore turns into melting of poor quality iron, which requires purification of additional processes.[6]
The alloying elements are added to pure molten for the purpose of improving the mechanical properties, and then pouring the molten in the casting machines to put it in the form required for its manufacture. The casting systems are different in their specifications, which include billets and slabs. This study focuses on casting the molten in the system of casting the veins. After casting the molten, it is subjected to various rolling processes and thermal and chemical treatments to put it in the final state of sale or use for the purposes for which it is manufactured.[6]
The second method is a method that begins with the purification of iron ore before the process of thermal extraction. Added to the reduced pellets to the electric arc furnaces to melt them to a temperature of up to 1600 ^oC to ensure that the molten reaches temperatures above

the melting point. From the electric arc furnaces, the molten add some alloy elements and the mixture is mixed for the purpose of chemical and thermal homogeneity. The homogeneous melt shall be transported chemically and thermally to the distributor. Through a number of lower openings of the distributor, the molten is added at a certain rate to the casting molds, through which the melt is frozen in the form of steel veins or slabs.[7]

1.2 Freezing Molten Steel in Casting Molds:

The casting system consists of molten steel, copper mold and cooling water. During the freezing process, the heat is transferred from molten to cooling water by the mold. There are some parameters that affect the freezing process, and on the thickness of frozen molten steel. These parameters are:

1.2.1 Temperature above fusion. (Liquid temperature):

Steel is just the element iron that has been processed to control the amount of carbon. Iron, out of the ground melts at around 1510^{o}C. Steel often melts at around 1460 ^{o}C. [15]. At this point, the temperature above the melting point should be sufficient to cover this lost heat during the casting process. In this study, the temperature above fusion will be changed, with fixing the value of other parameters such as mold thickness, thermal conductivity of mold, and thermal conductivity of molten steel.

1.2.2 Effect of thermal conductivity of copper mold:

The thermal conductivity expresses the ability of the metal to conduct heat and is related to the interference of atoms in the metal when it is shaken as a result of high temperature. Three metals of the casting mold used in this study are structural steel, aluminum, and copper, where thermal conductivity changed from 44, 238, and 398 respectively, with fixing the value of other parameters such as temperature over melting, mold thickness, and thermal conductivity of molten.

1.2.3 Effect of the thickness of the casting mold:

It is known that the rate of heat transfer is inversely proportional to the thickness of the conductive layer. As stated in the Fourier Act I, [8].

$$Q = k\,\frac{\Delta T}{-\Delta X}$$

Q represents the thermal flux, (W/m^2), k is the thermal conductivity,(W/m.^{o}c) and ΔT represents the temperature gradient (^{o}C). The thickness of the casting mold will be changed when calculating the thickness of the frozen molten layer, with the fixation of the melting point temperature and the thermal conductivity of the mold and thermal conductivity of the steel molten. In this study, the thermal conductivity (w/m.K) of the molten steel, [8] will be changed with the fixation of the melting point, mold thickness, and thermal conductivity of the mold at certain values.

1.3. The thickness of frozen molten steel:

When the casting mold is cooled by water, the heat transfers from the molten steel to the casting mold to the cooling water. At this point, the molten steel starts to freeze and forms a frozen layer. The thickness of this frozen layer increases with the cooling rate increasing.

1.4 Importance of frozen molten thickness:

The thickness of the frozen layer gives this research an impression of the mechanical properties of the metal, In other words The increase in the thickness of the frozen layer of molten metal means a rapid rate of solidification, which means the production of fine granular structures with better mechanical properties, and vice versa. [14]

1.5. The heat transfer:
In the cooling process of the casting system, the heat is transferred from the molten to the casting mold by conduction and from the casting mold to the cooling water by convection

1.5.1 Conduction:
Conduction is reliant upon physical contact. If there is no contact, conduction cannot take place. Contact between two substances of different temperature results in a heat transfer from the higher temperature to the lower temperature substance. The greater the temperature differential, the faster the heat exchange.

1.5.2 Convection:
Convection is the transfer of energy via fluids (gases and liquids). It is this method that plays the greatest role in the transfer of heat in casting system. [8]

1.6. Problem Statement:
The casting system consists of molten steel, casting mold and cooling water. During freezing, heat is transferred from molten to cooling water by casting molds.
The thickness of the frozen layer can help this research to determine the microscopic structure and mechanical properties of the cast metal. The increase in the thickness of the frozen layer of the molten metal means a rapid solidification rate, means produce fine grains structures with better mechanical properties, and vice versa. This research can identify the thickness of the frozen layer of molten steel if this research can investigate the effect of some of the active parameters during the process of casting and cooling. Since the experimental investigation of this process cannot be carried out because of the temperature rise to 1600 ° C, and the difficulty of any direct measurements of the parameters affecting the freezing process, this research are to resort to simulation process. The simulation aims to use the mathematical method to study the thickness sensitivity of the frozen layer of molten steel in casting molds to some of the parameters affecting it as these parameters change in a given range.[9]
If this research can determine the temperature of each cell or node within the molten steel during the cooling period this research can obtain the thickness of the frozen layer of molten steel, and also this research can know the microscopic structure of frozen molten steel during cooling.

1.7. Objectives:

- To show the quality of final casting mainly depends on the rate of solidification as rapid solidification produces fine grains structures with better mechanical properties, [14].
- To show the thickness of the frozen layer of molten metal in casting gives this research an indication about the rate of solidification.
- To show the increase in this thickness means a rapid solidification rate, means produce fine grains structures with better mechanical properties, and vice versa.
- To simulate the freezing process of molten steel in casting molds and determine the effect of some parameters such as temperature above fusion for steel, thermal conductivity of molten steel, mold thickness, thermal conductivity of mold that on frozen layer thickness of molten steel, and the sensitivity of the thickness of this frozen layer for these parameters.

- To determine the thickness of the frozen casting layer, as well as determine the values of the appropriate parameters.
- To obtain optimum thickness for this theoretically frozen layer. This is the solution to the difficulty of conducting this study experimentally.

2 - LITERATURE REVIEW

Madhusudhan, [10]. The study of rate of solidification of centrifugal casting is highly impossible by direct measurement, based on grain size the solidification rate can be easily determined. Grain size has been measured for the gravity castings at different cooling rates and using this result rate of solidification of the centrifugal castings have been determined which are produced at different rotational speeds. The slow rate of solidification gives coarse grains and faster rate of solidification gives fine equi-axed grains. At around 400 rpm due to turbulence the rate of solidification is faster and hence the fine grains are formed and at very low and around 800 rpm the rate of solidification is slightly slower and hence coarse grains are formed.

Madhusudhan, [11]. Effect of mould wall thickness on microstructure of centrifugal casting has been studied. The centrifugal cast sample shows a fine to coarse microstructure from the outer to inner casting surface. Mould wall thickness is one of the parameter which affects the rate of solidification. As the thickness of mould increases the solidification takes place at faster rate. This is due to the chilling effect of the mould. The chilling effect on the casting depends on thermal mass of liquid metal and relative movement between the liquid metal and inner surface of the mould. Rapid solidification shows the well distributed fine grains and slow solidification rate shows coarse grain size. The experimental details can be the basis for the more advanced researchers.

Katsina Christopher [12]. The analysis of heat transfer during the casting and solidification of aluminum alloy as well as the experimental investigation of the rate of solidification in varying thicknesses of cylindrical metallic mould was carried out. The experimental results have shown that mould thickness has influence on the solidification time of aluminum casting. Solidification time is longer for cylindrical mould with smaller mould thickness. As the thickness of mould increases solidification takes place at faster rate. This is due to the chilling effect of the mould which is also dependent on the heat content of the molten metal.

Bala K. C. [13]. This paper presents the influence of mould thickness and temperatures on the solidification time of aluminum (Al-3.42%Mn; 2.38%Ni; 0.26%Si) alloy in rectangular metallic moulds. Experiments were conducted to measure the temperature fields in a solidifying casting against time. From the temperature fields solidification times were obtained for various moulds thicknesses as well as the mould temperatures. The results presented that mould thickness has significant influence on the solidification time. Smaller mould thickness produced shorter solidification time within the experimental specification. As the mould temperatures are increased the solidification time is prolonged and this influence grain development during the solidification process subsequently affecting the mechanical properties of the castings produced.

S. Ilangovan, [14]. An investigation was carried out to understand the effects of solidification time of the cylindrical specimen on hardness, wear rate and the coefficient of friction of Aluminum alloy (LM4). The commercially available LM4 Aluminum alloy was melted in a crucible furnace under argon atmosphere. The molten metal was poured into sand moulds having dissimilar size holes. The cast rods were tested for Vickers micro-hardness, wear rate and the coefficient of friction. The solidification time increases from 0.22 to 0.61 seconds when the diameter varied from 20 to 35mm. It was found that the hardness of the alloy vary with the diameter of the rod. Wear rate is inversely proportional to the hardness of the alloy. It was observed that the yield strength and tensile strength are increases with hardness, whereas the % elongation decreases. Further, the coefficient of friction is independent of hardness and not affected by the sliding time. Wear rate decreases linearly with hardness.

Therefore the understanding of the effect of some of parameters as: mould thickness, temperature above smelting, thermal conductivity of molten steel, and thermal conductivity of mould can be a useful tool with which to improve process design and in turn control product quality. So this study assessed the effect of these parameters on the thickness of frozen molten steel layer of a rectangular veins cast to help improve casting process thereby producing high quality products.

3. METHODOLOGY

This research can use the Heat Transfer Module to model this type of phase change. In the continuous casting process, liquid metal is poured into a cooled mold and starts to solidify. As the metal leaves the mold, the outside is solidified completely, while the inside is still liquid. To further cool down the metal, spray cooling is used. When the metal is completely solidified, it can be cut into billets. This is a stationary, time-invariant, process. The rate at which the metal enters and leaves the modeling domain does not vary with time, and neither does the location of the solidification front.

The casting system consists of molten steel, mold and cooling water. During freezing process, heat is transferred from molten to cooling water by casting mold. Since it is not possible to carry out a practical study of this process due to high temperatures up to 1600 degrees Celsius, and in addition to the difficulty of any direct measurements of the parameters affecting the freezing process, this research resort here to the simulation of this process. The simulation process here is intended to use the mathematical method to study the sensitivity of frozen molten layer thickness to some of the parameters affecting it as these parameters are changed in a specific range.

At this point, is an illustration of the continuous casting process:

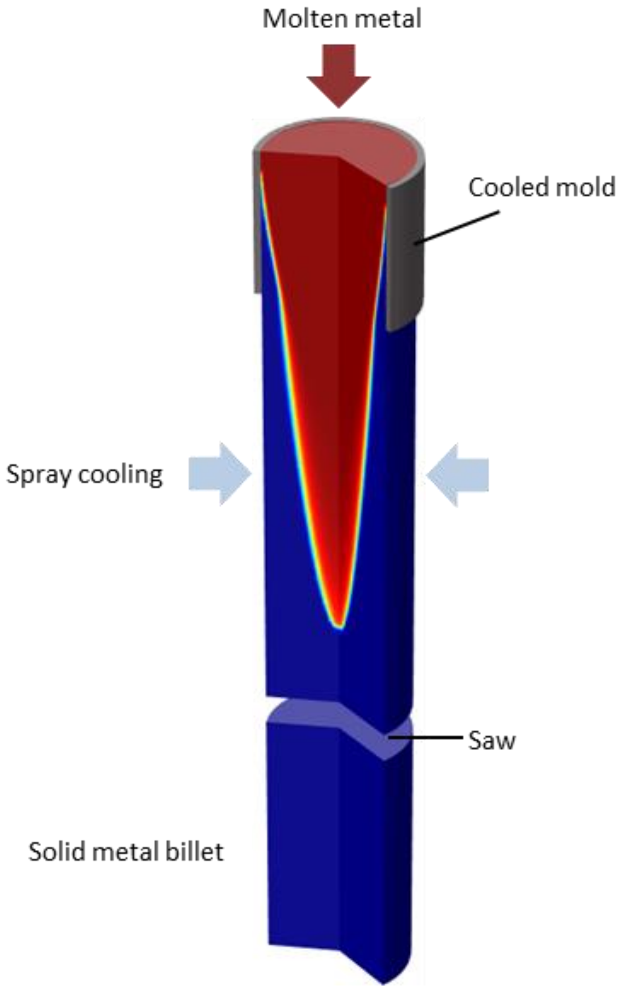


Figure. 3.1. Sketch of a continuous casting process.

In order to optimize and improve this process, this research can turn to simulation. With COMSOL software, this research can predict the exact location of the phase interface.

Modeling Phase Change with the Apparent Heat Capacity Method

COMSOL Multiphysics and the Heat Transfer Module together offer a tailored interface for modeling phase change with the *Apparent Heat Capacity method*. The method gets its name from the fact that the latent heat is included as an additional term in the heat capacity. This method is the most suitable for phase transitions from solid to solid, liquid to solid, or solid to liquid. Up to five transitions in phase per material are supported. The latent heat of freezing, crystallization or solidification is the amount of energy released from freezing unit mass of a saturated liquid

For this work, **ComsolMultiphysics 5.4 software** is employed for the numerical investigation of the freezing process of molten steel in casting molds and determine the effect of some parameters on frozen layer thickness of molten steel

3.2 Physical concepts:

3.2.1 Heat transfer:

The heat transfer phenomena in the casting process are modeled in two different ways depending on the phase of the material (i.e, if the material is in a solid or liquid state). In the model, the mold is modeled as a solid throughout the whole simulation. The steel is initially modeled as afluid, but as it cools down it turns into a solid (see *3.2.2 Phase change*).

Solids

The solid parts of the model are the mold and the casting itself after solidification. The heat transfer process for the solid parts in the model is defined according toEq. 1 (COMSOL, 2018c) ,[3].

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T + Q \qquad (3.1)$$

Where ρ is the density, C_p is the apparent heat capacity at constant pressure, *k* is the effective thermal conductivity, T is temperature, and Q is the heat source.
The specific heat cp in the casting iron is determined based on Eq. 4 (Spakovszky, 2007).

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p \qquad (3.2)$$

h: the enthalpy of an element: is the heat energy or amount of heat that a substance contains
Note that this correlation is valid under the assumption that there is no pressure change in the substance.

Fluids
The heat transfer in the fluid module is used in the casting during the phase change. COMSOL defines the heat transfer process in fluids according to Eq. 3.3 (COMSOL, 2018c).

$$\rho C_p \frac{\partial T}{\partial t} = k\nabla^2 T - \rho C_p \mathbf{u}\nabla T + Q + Q_p + Q_{vd} \qquad (3.3)$$

In the casting mold, the velocity u is determined by the turbulent flow module, Q_p is the pressure work (w/m3), and Q_{vd} is the viscous dissipation (w/m3). Since all material used in the model is considered as incompressible and the pressure is assumed constant, the stress tensors and thermal expansions can be neglected. Consider the stationary heat transfer equation with a convective term, steady state, and without heat source [3] :

$$\rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k\nabla T) \qquad (3.4)$$

3.2.2 Phase change:
The solidification of a single material occurs at a specific temperature. However, this is not the case in castings since the material used often is a mix of different components. Instead, the phase change occurs over a temperature interval. This interval is limited by the liquidus and solidus temperatures, or T_L and T_S, respectively (Askeland and Wright, 2017). In this interval, some of the material properties can be determined using the *apparent heat capacity method*. This method uses the fraction of material in liquid state, expressed as the smoothed function Θ(T), and the material properties for the solid and liquid phases to get a weighted mean value for the casting (Bannach, 2014). Θ is shown in Fig. 3,2, where Θ_1 is equal to Θ and Θ_2 is equal to 1- Θ. The interval $\Delta T_{1\to 2}$ is limited by T_L and T_S, and $T_{pc;1\to 2}$ is the mean value of T_L and T_S (Bannach, 2014).

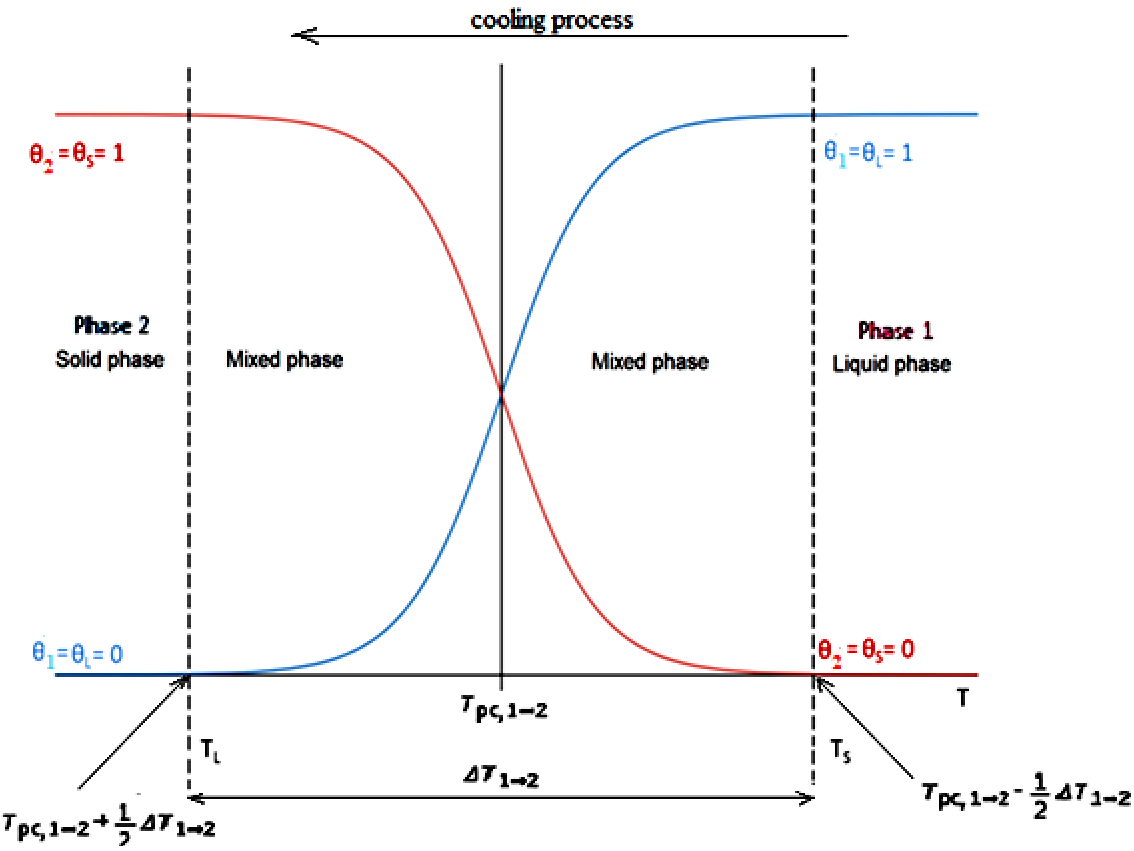


Figure 3.2: Phase indicators, phase change temperature, and transition interval, and the function Θ (T) that COMSOL uses during the phase change.

In COMSOL, the phase transition of the casting is a sub node to the heat transfer module. The Θ (T) function is used by COMSOL to determine the specific heat, thermal conductivity and density during the phase change according to Eqs. 5-7.

$$c_p = \frac{1}{\rho}(\theta_1 \rho_{ph1} c_{p,ph1} + \theta_2 \rho_{ph2} c_{p,ph2}) + c_L \qquad (3.5)$$

$$k = \theta_1 k_{ph1} + \theta_2 k_{ph2} \qquad (3.6)$$

$$\rho = \theta_1 \rho_{ph1} + \theta_2 \rho_{ph2} \qquad (3.7)$$

Since the density of the iron is assumed to be constant due to the constant volume and conservation of mass, $\rho_{ph1} = \rho_{ph2} = \rho$.
c_L in Eq. 5 represents the *latent heat distribution*, which is the specific heat released from the casting due to the phase transition. The latent heat distribution is approximated in COMSOL as Eq. 8 (COMSOL, 2018c).

$$c_L(T) = L\frac{d\alpha_m}{dT} \qquad (3.8)$$

L denotes the *latent heat of melting*, and _m is the mass fraction of the liquid phase during the phase transition. α_m is dependent of *Θ* as described by Eq. 9.

$$\alpha_m = \frac{1}{2}\frac{\theta_2 \rho_{ph2} - \theta_1 \rho_{ph1}}{\rho} \qquad (3.9)$$

Material parameters regarding the phase change are presented in Table (3.1).

Table 3.1: Phase change parameters for the casting steel.

Parameter	Value
T_L	1460 °C
T_S	1388 °C
L	260 kJ/kg

3.3 Methods:

The methodology followed in this work targeted the modelling of the freezing process of molten steel in casting molds and determine the effect of some parameters on frozen layer thickness of molten steel, and the sensitivity of the thickness of this frozen layer for these parameters. These parameters are temperature above fusion for steel, thermal conductivity of molten steel, mold thickness, thermal conductivity of mold that. For this purpose twelve different model designs were developed in COMSOL Multiphysics:

- The effect of temperature above fusion, which was changed according to the values(1600^{o}C, 1550^{o}C, 1500^{o}C) with fixing the other parameters such as the thermal conductivity of the mold, he thickness of the mold, and the thermal conductivity of the molten.
- The thermal conductivity of the mold was changed according to the values (44 structural steel, 238 Aluminum, 398 Copper) with fixing the rest of the other parameters.
- The mold thickness was changed according to the values (3mm, 6mm, 10mm) with fixing the rest of the other parameters.
- And the thermal conductivity of the molten was changed according to the values (50, 86, 150) with fixing the other parameters.

3.4. Numerical model:

To study the sensitivity of the frozen layer thickness to some of the parameters affecting it, 2D geometry was employed r direction and z direction, while a time-dependent study was chosen to satisfy the non-steady nature of the problem. The study also employed the Conjugate Heat Transfer module and the Heat Transfer with Phase Change feature to enable the examination of the transient temperature transfer in the molten steel in the casting mold. Appropriate boundary conditions were also used to represent the experimental conditions in casting process.

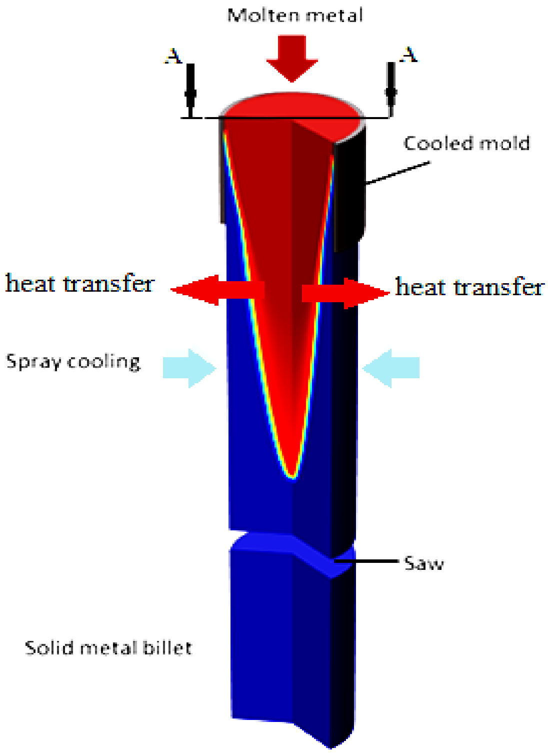


Figure. 3.3. Longitudinal section A-A in casting mold of casting system

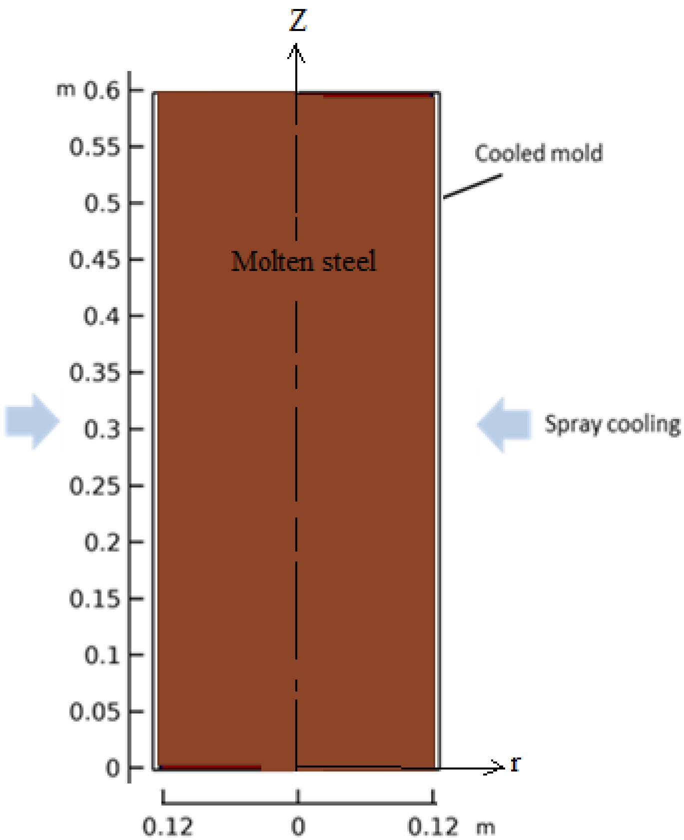


Figure. 3.4. The section A-A as shown above.

3.4.1 Geometry and materials:

Figure 3,3 represents the two-dimensional (2D) geometry that was employed in COMSOL Multiphysics for the simulation of the Process of Freezing Molten Steels in Casting Molds, and Identify the Important Parameters Actually Affecting this Process.
Three materials of casting mold (structural steel, aluminum, and copper) was employed in COMSOL Multiphysics.
The casting mold where the steel poured is 0.12 m radius, 0.6 m deep and (3mm , 6mm , 10mm) thickness, as shown in Figure 3.3. Table 3.2 and 3.3 outlines the thermophysical properties of the above materials.

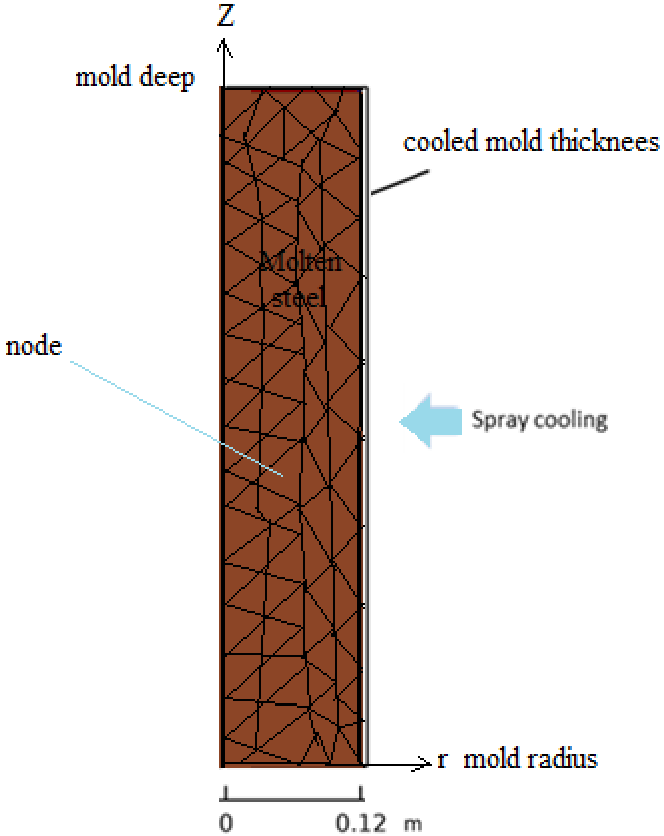


Figure. 3.5. Geometry and mesh of tow-dimensional (2D) numerical models developed in COMSOL Multiphysics.

Table. 3.2: Values of the parameters employed for the numerical simulation study

Parameter	symbol	Value	Unit

Temperature above Fusion (superheat)	T_cast	1600, 1550, 90, 1500	˚C
Mold thermal conductivity, (Three metals mold used : structural steel, aluminum, and copper)	K_m	44, 238, 398	W/m.°C
Mold thickness	t_m	10, 6, 3	mm
Molten Steel thermal conductivity	K_liquid	50, 86, 150	W/m.°C
Casting speed	V_cast	5	mm/s
Mould radius	r	120	mm
Mould deep	Z	600	mm

Table. 3.3: Thermophysical properties of ASTM A36 carbon steel (SS400, S275) materials employed for the numerical simulation study, [1]

Property	**symbol**	**Value**	**Unit**
Melting point	T	1460	°C
Latent heat of solidification	L	260	kJ/kg
Solid heat capacity at 25°C	C_p	0.47	kJ/.kg. °C
Liquid heat capacity above 1460°C	C_p	0.76	kJ/.kg. °C
Solid density at 25°C	ρ_{solid}	7900	kg/m^3
Liquid density above 1460°C	ρ_{liquid}	7135	kg/m^3
Solid thermal conductivity	K_{solid}	50	W/m.°C
Liquid thermal conductivity	K_{liquid}	86	W/m.°C

3.4.2. Boundary conditions:

For the numerical simulations, transient modelling for conjugate heat transfer in solids and liquids was adopted, in addition to the phase change feature of the Heat Transfer module of COMSOL Multiphysics. The thickness of the steel frozen layer in the casting mold was set to change phases throughout the simulation according to the properties given in Tables 3.2, and 3.2.

The Some initial parameters for both the molten and the casting mold were defined. The boundary conditions for some parameters, which affect the thickness of the frozen layer, was exposed to, were inserted as an interpolation in the simulation study and are illustrated in Tables 3.2, and 3.3.

3.4.3 Meshing:

It was determined that the most appropriate mesh for this model was a free Mono meshing. The mesh type was set to physics- controlled and its size was set to normal. There were hundreds of elements used for the simulation of 3 days of transient heat transfer.

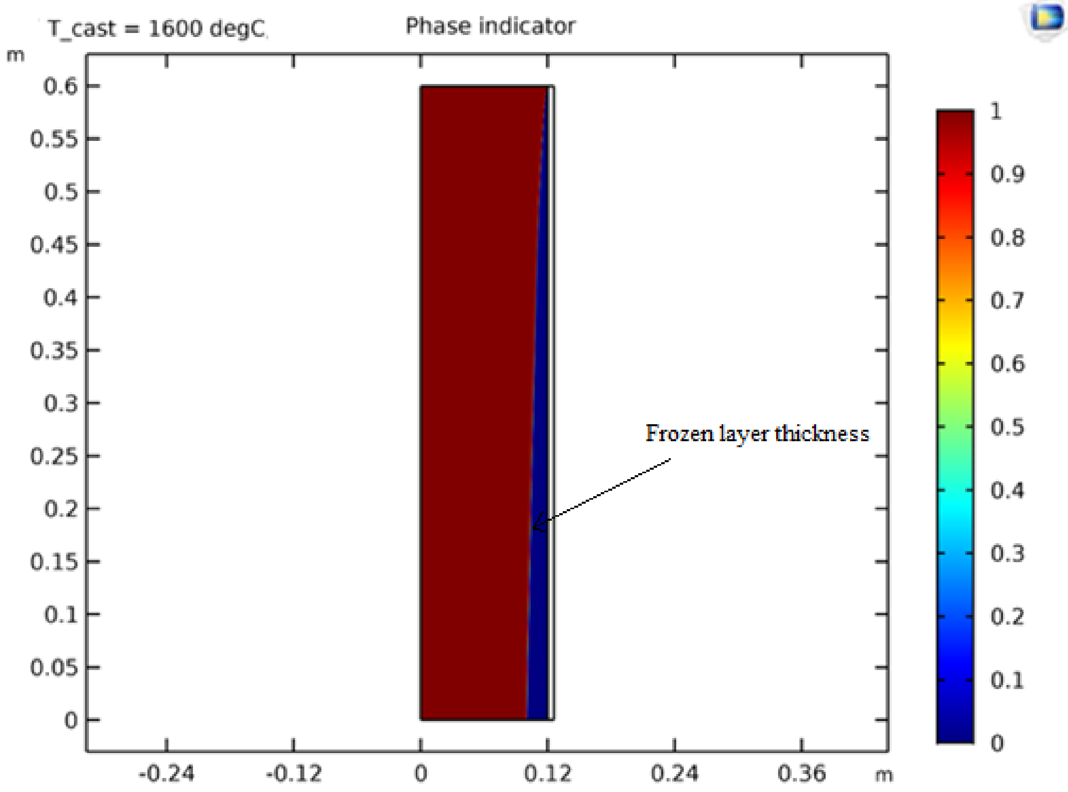
4.1 Results:

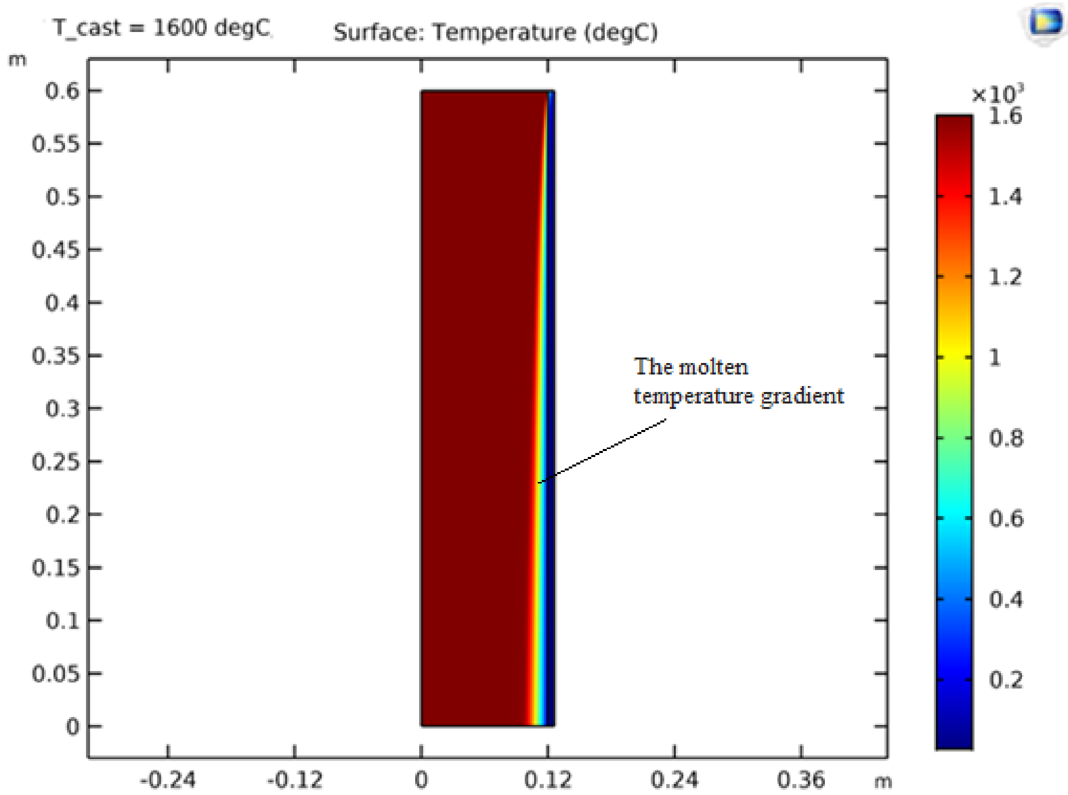
These results were obtained, which show the effect of some parameters on both the thickness of the frozen layer (the solidification rate) and the gradient of the molten temperature during

the casting process, where in each case this research changed one of the parameters and fixed the rest of the other parameters, and accordingly the diagrams in paragraph 2.4. It shows this research the effect of temperature above fusion, which was changed according to the values (1600°C, 1550°C, 1500°C) with fixing the other parameters such as the thermal conductivity of the mold, the thickness of the mold, and the thermal conductivity of the molten.
And in the paragraph 3.4 the thermal conductivity coefficient of the mold was changed according to the values (44 structural steel, 238 Aluminum, 398 Copper) with fixing the rest of the other parameters, and in the paragraph 4.4 the mold thickness was changed according to the values (3mm, 6mm, 10mm) with fixing the rest of the other parameters And in the paragraph, 5.4 the coefficient of thermal conductivity of the molten was changed according to the values (50, 86, 150) with fixing the other parameters.

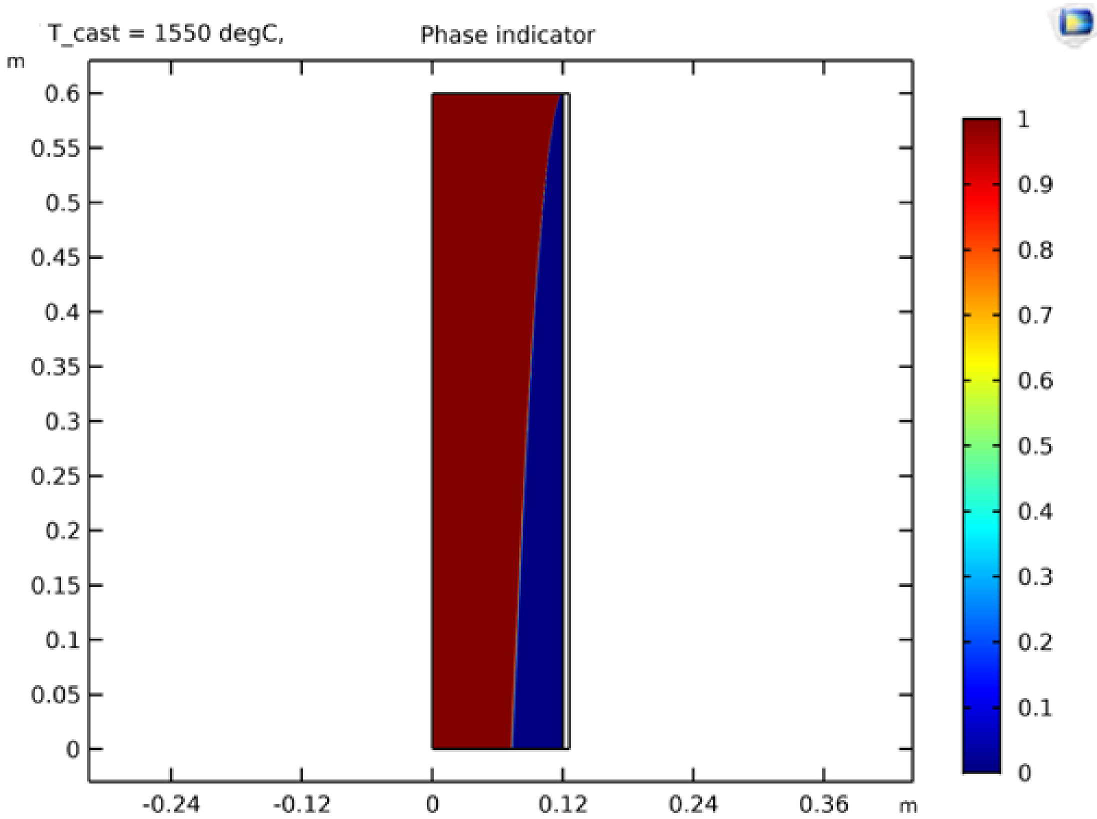
Appendix A illustrates the use of the mathematical program with the name ComsolMultiphysics 5.4 software in calculating one of the cases, which is the case in which the thermal conductivity of the casting mold has been changed.

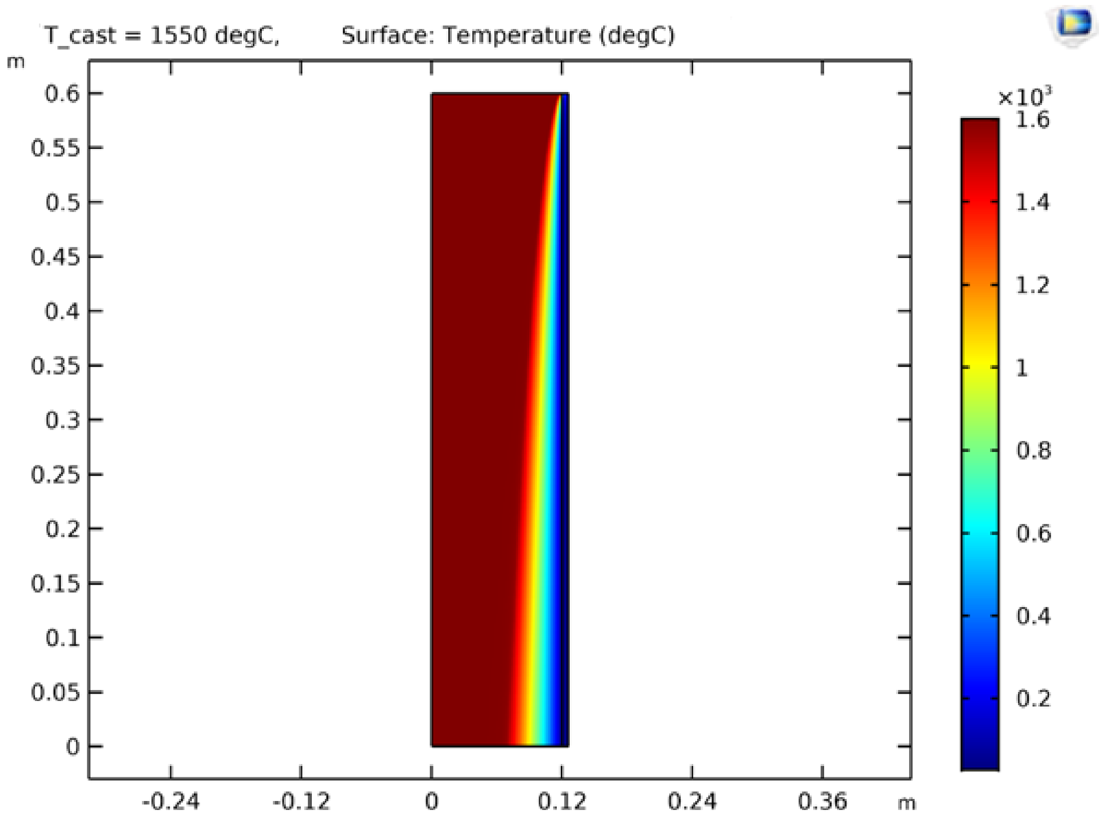
4.1.1 The effect of Temperature above Fusion :
T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, K_liquid = 86 W/m.K, k_m = 398 W/m.K



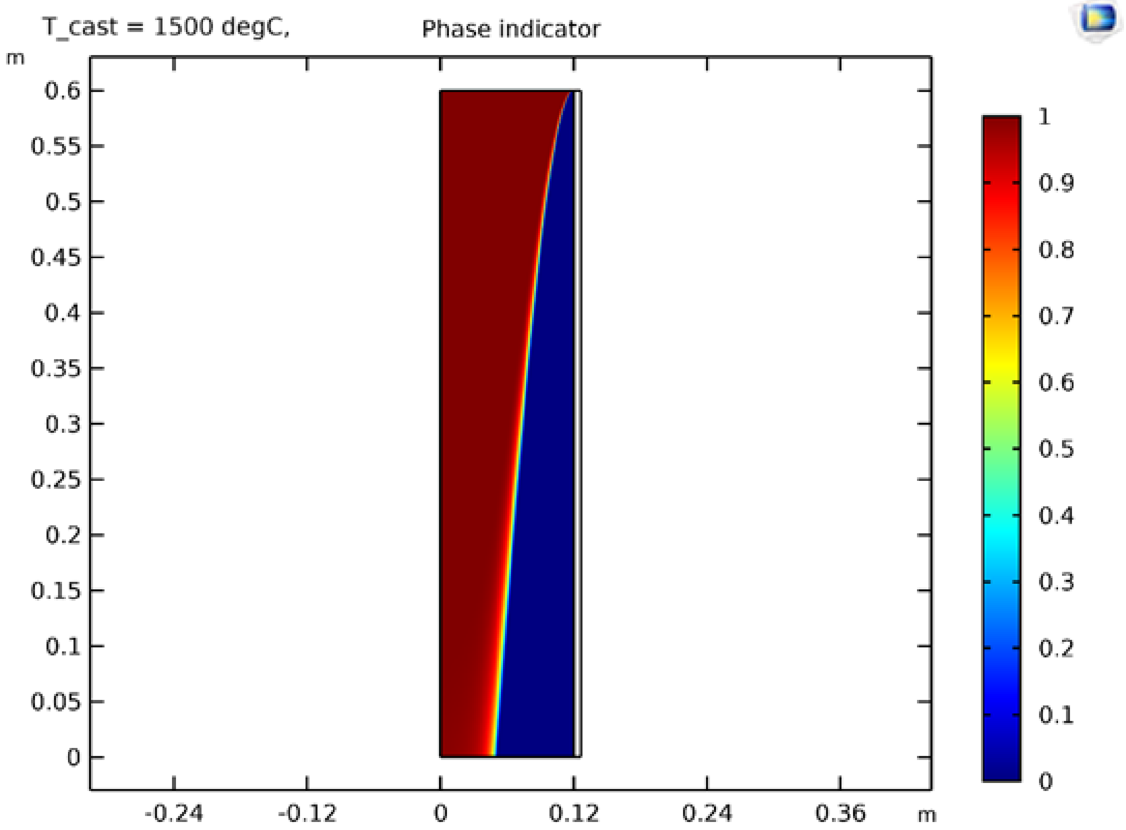


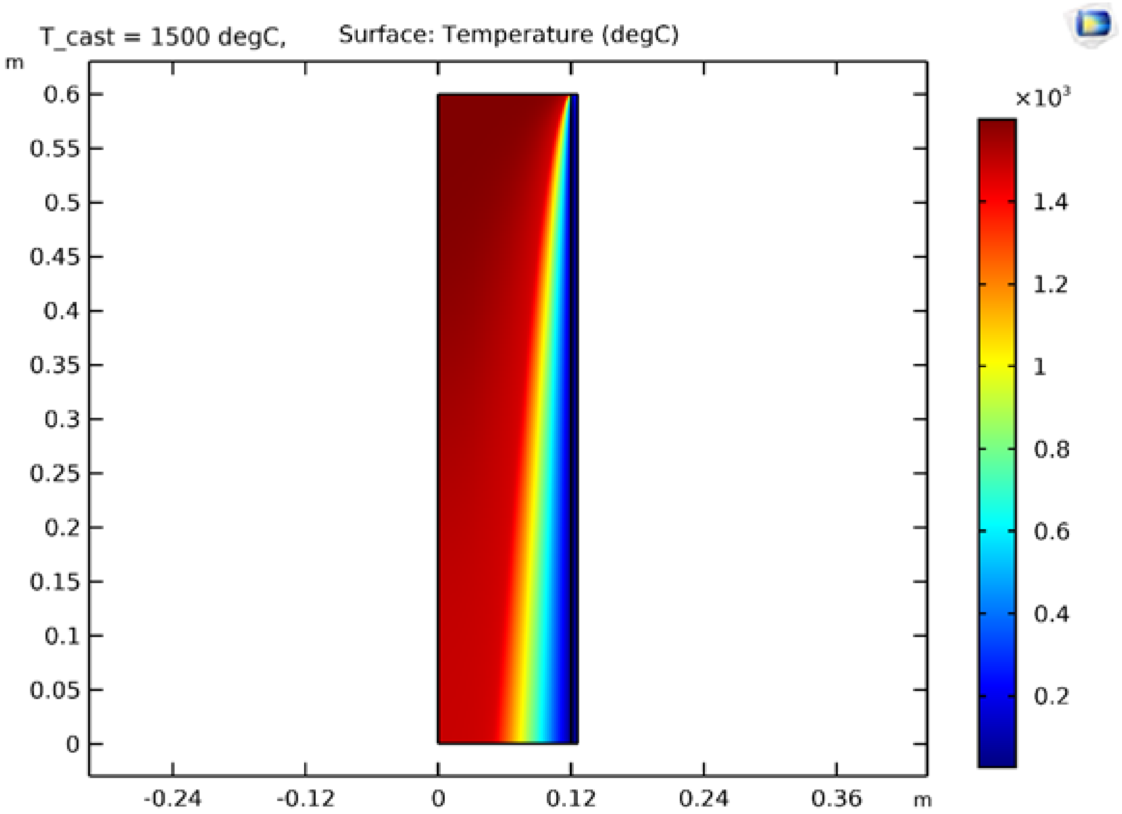
T_cast = 1550 °C, V_cast = 5 mm/s, t_m = 6mm, K_liquid = 86 W/m.K, k_m = 398 W/m.K





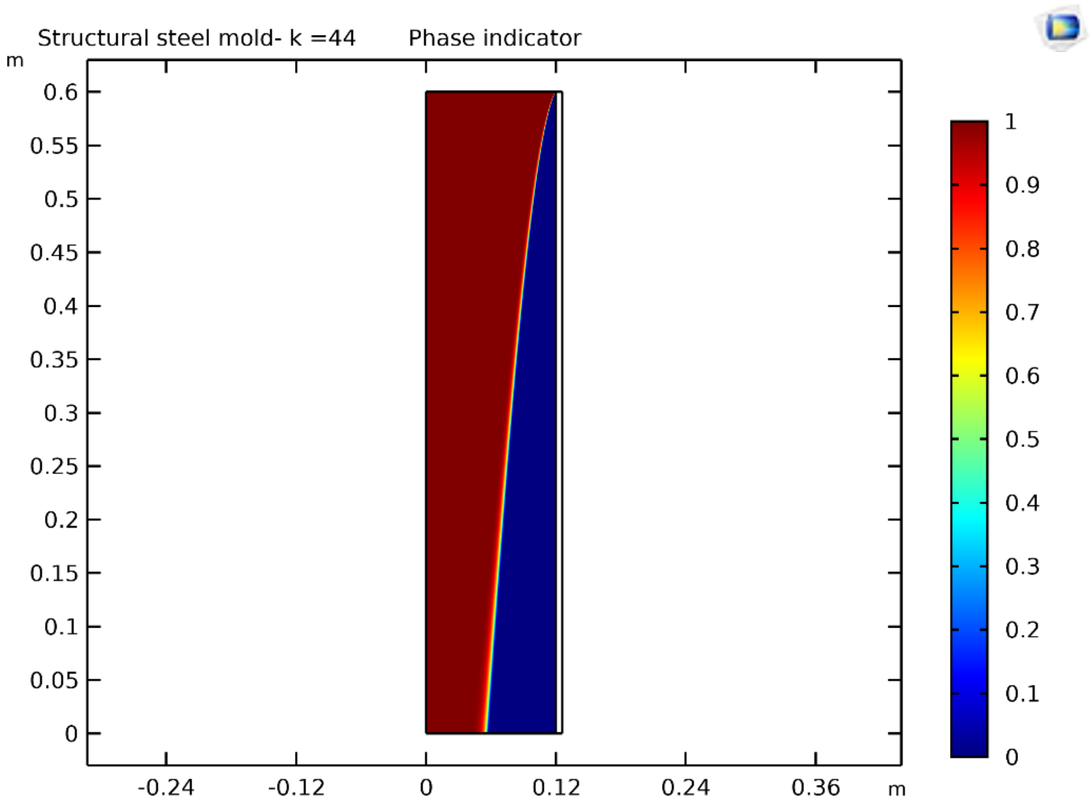
T_cast = 1500 °C, V_cast = 5 mm/s, t_m = 6mm, K_liquid = 86 W/m.K, k_m = 398 W/m.K

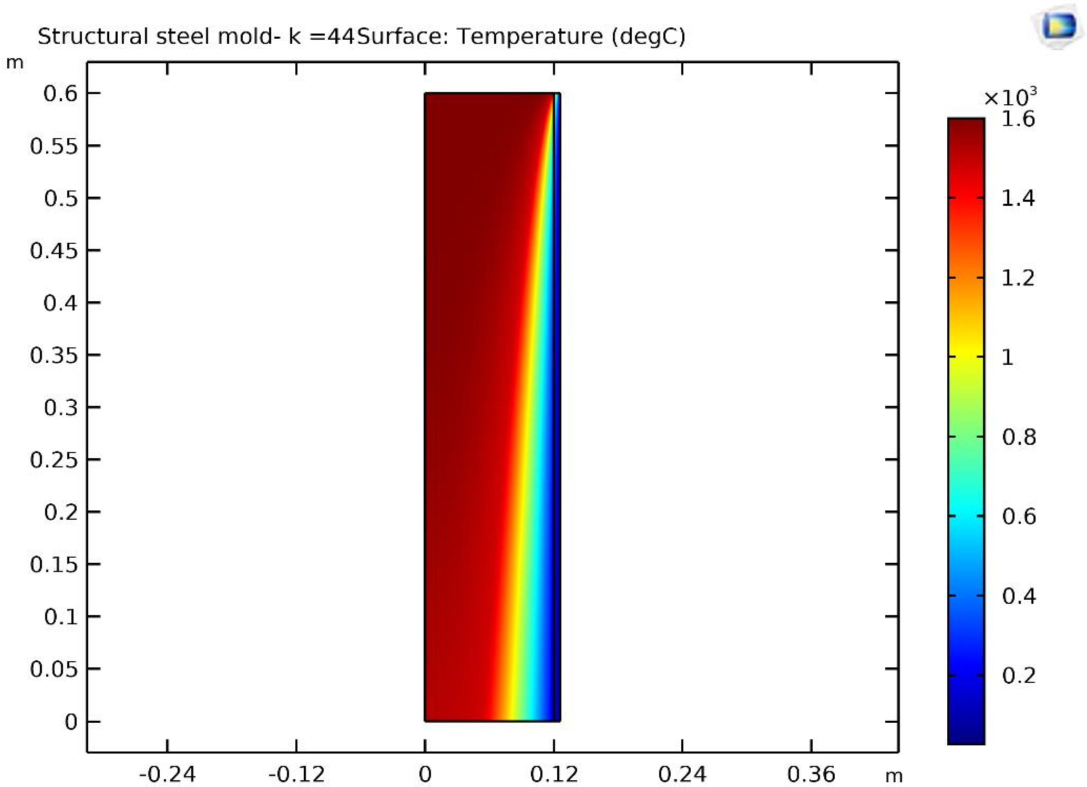




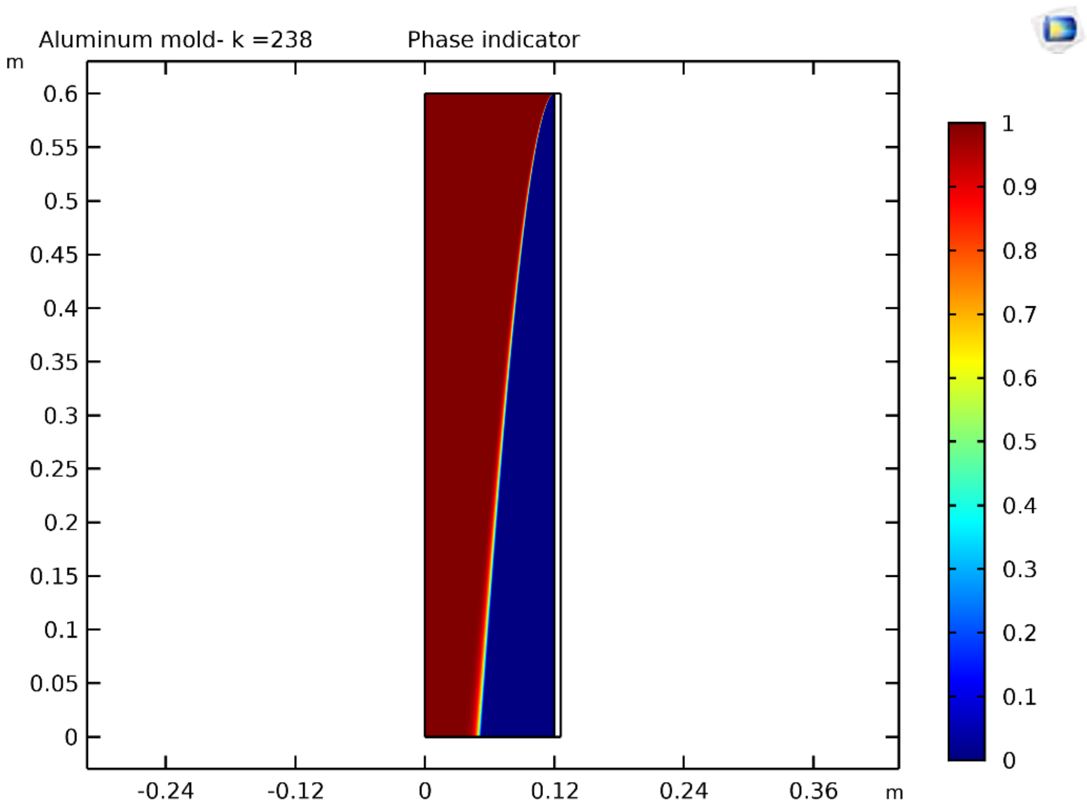
4.1.2 The Effect of Thermal Conductivity of the Casting Mold:

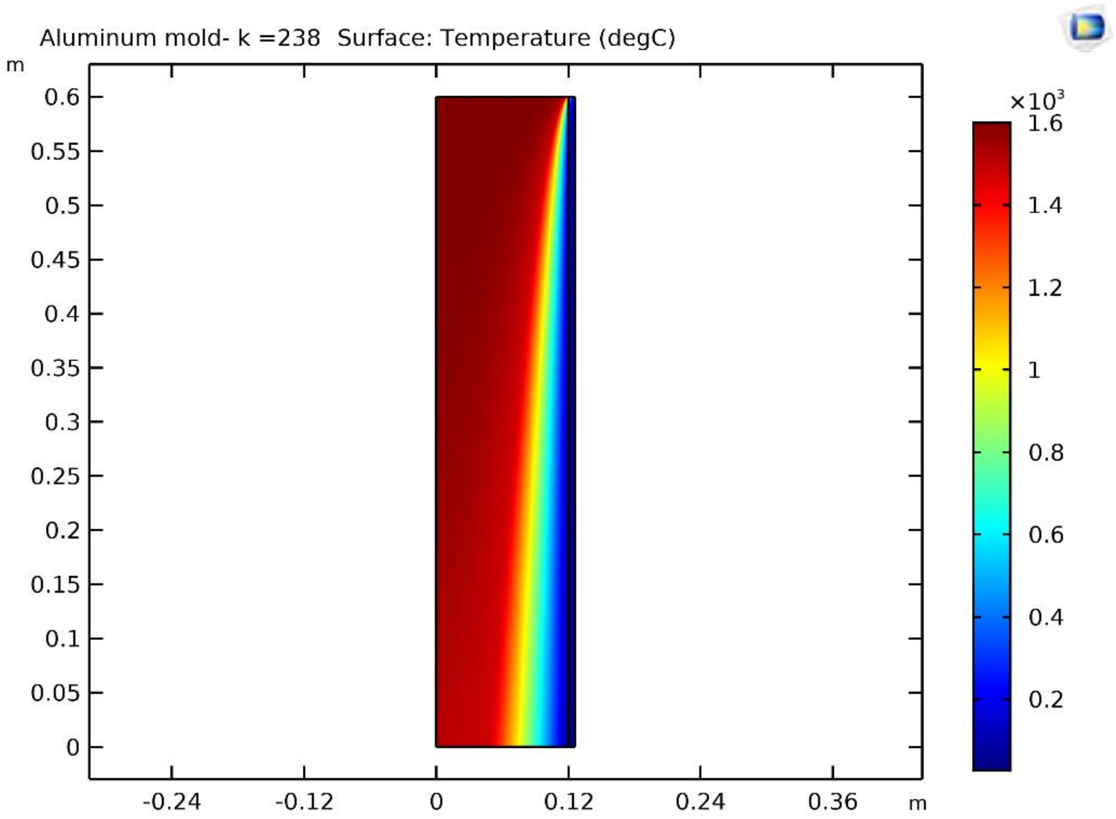
T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, K_liquid = 86 W/m.K, **K_m =44 W/m.K**.



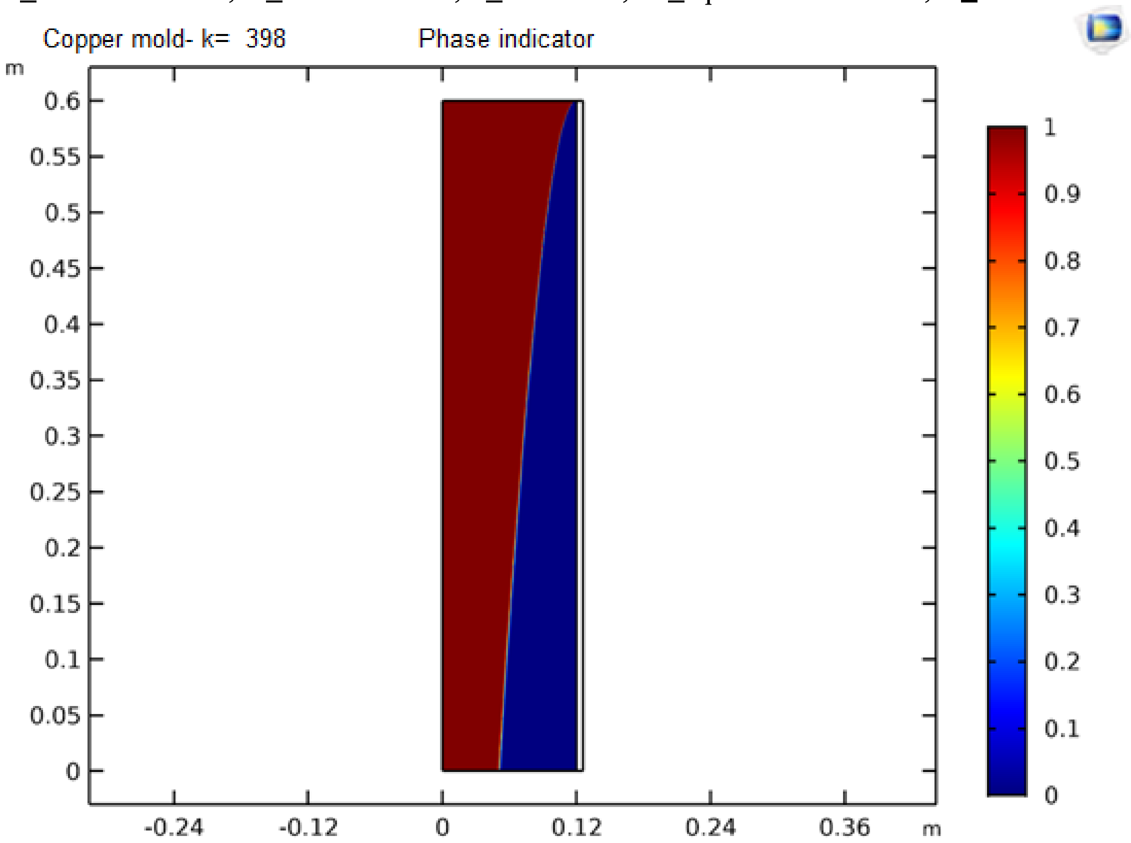


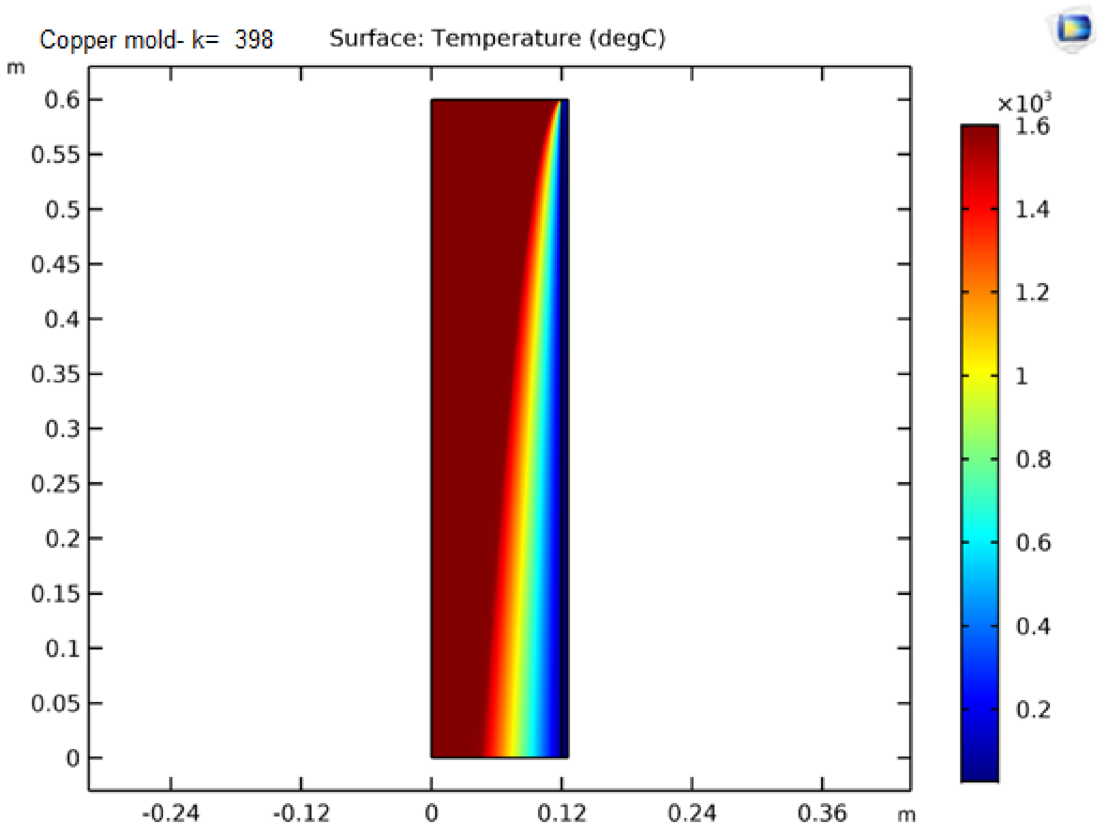
T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, K_liquid = 86 W/m.K, **K_mold =238 W/m.K**.





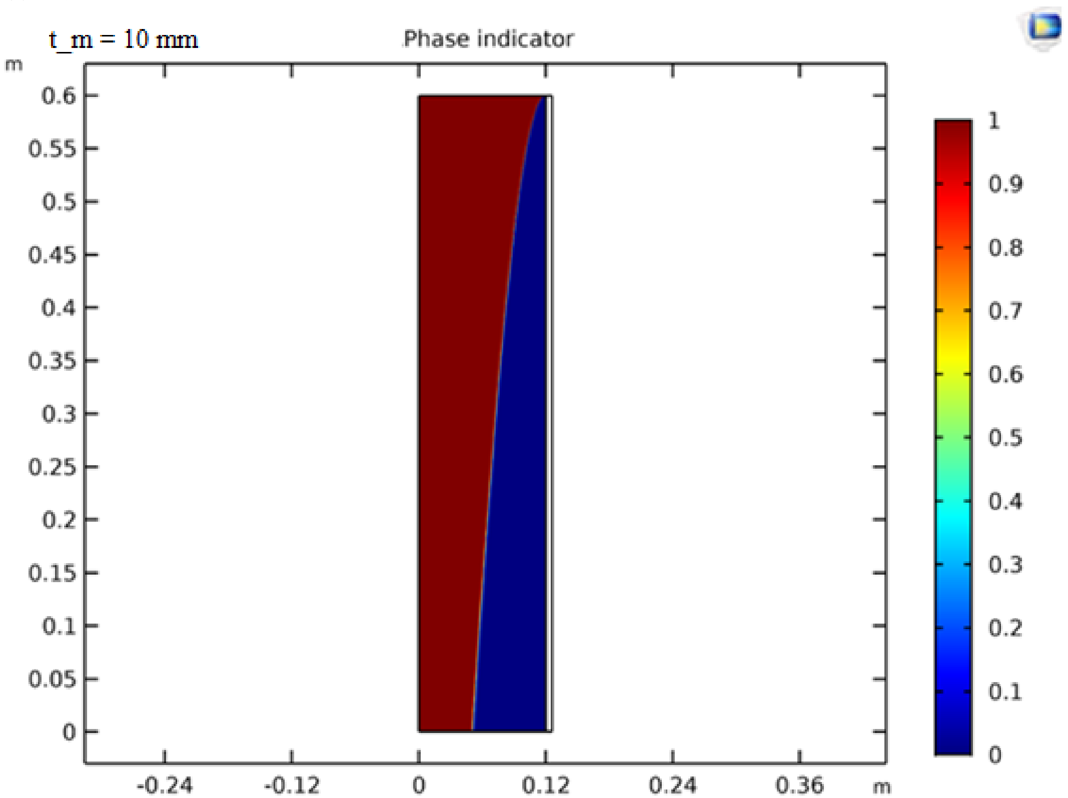
T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, K_liquid = 86 W/m.K, **k_m = 398 W/m.K**

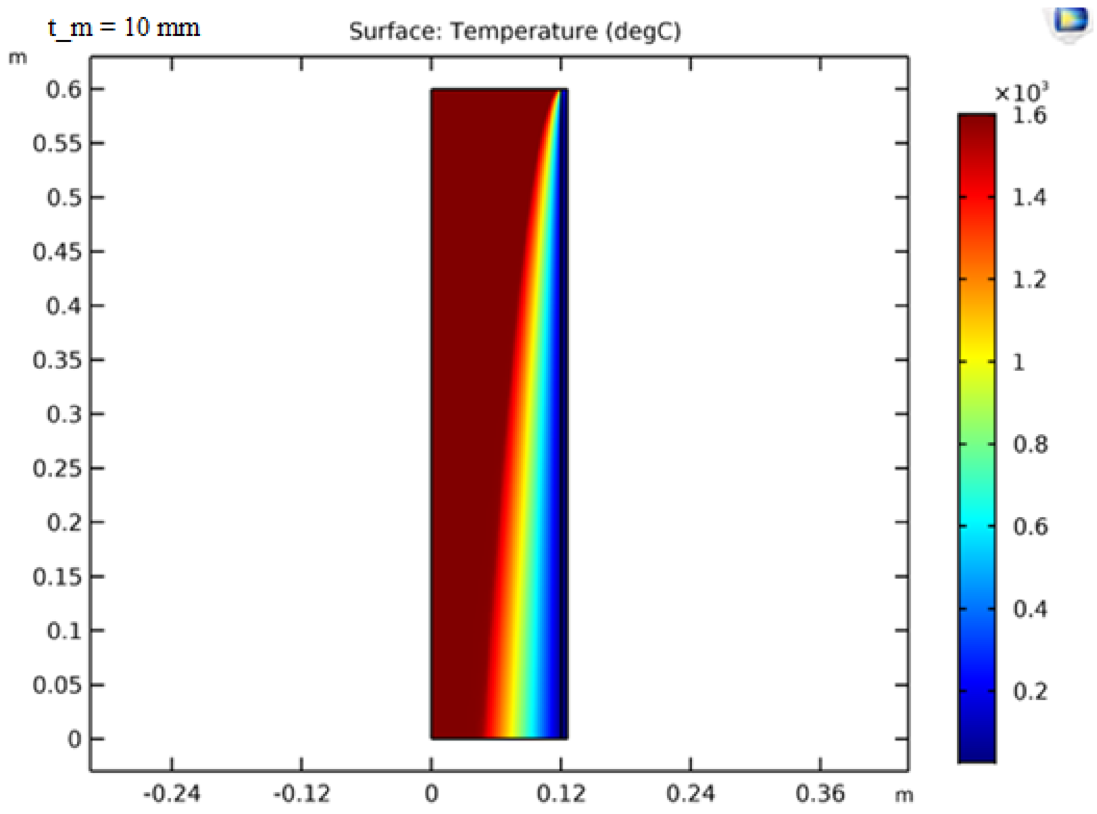




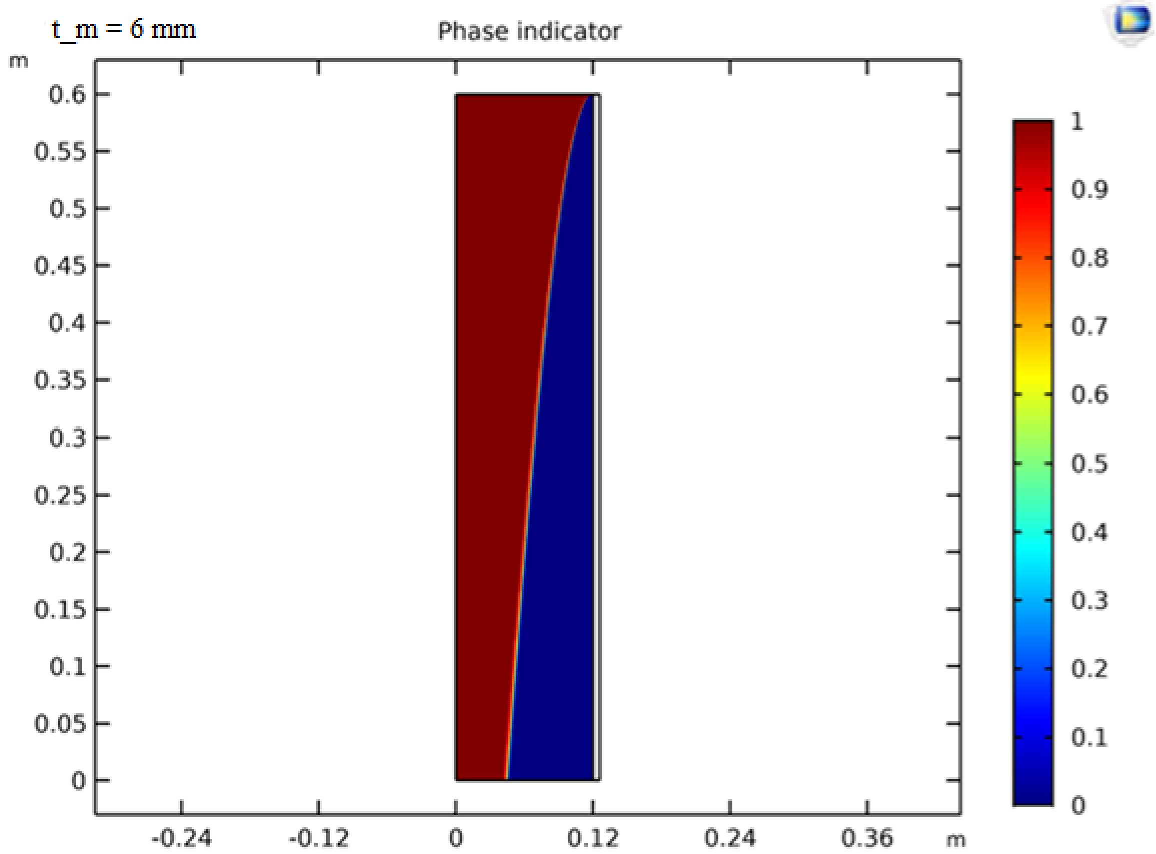
4.1.3 The Effect of Mold Thickness :

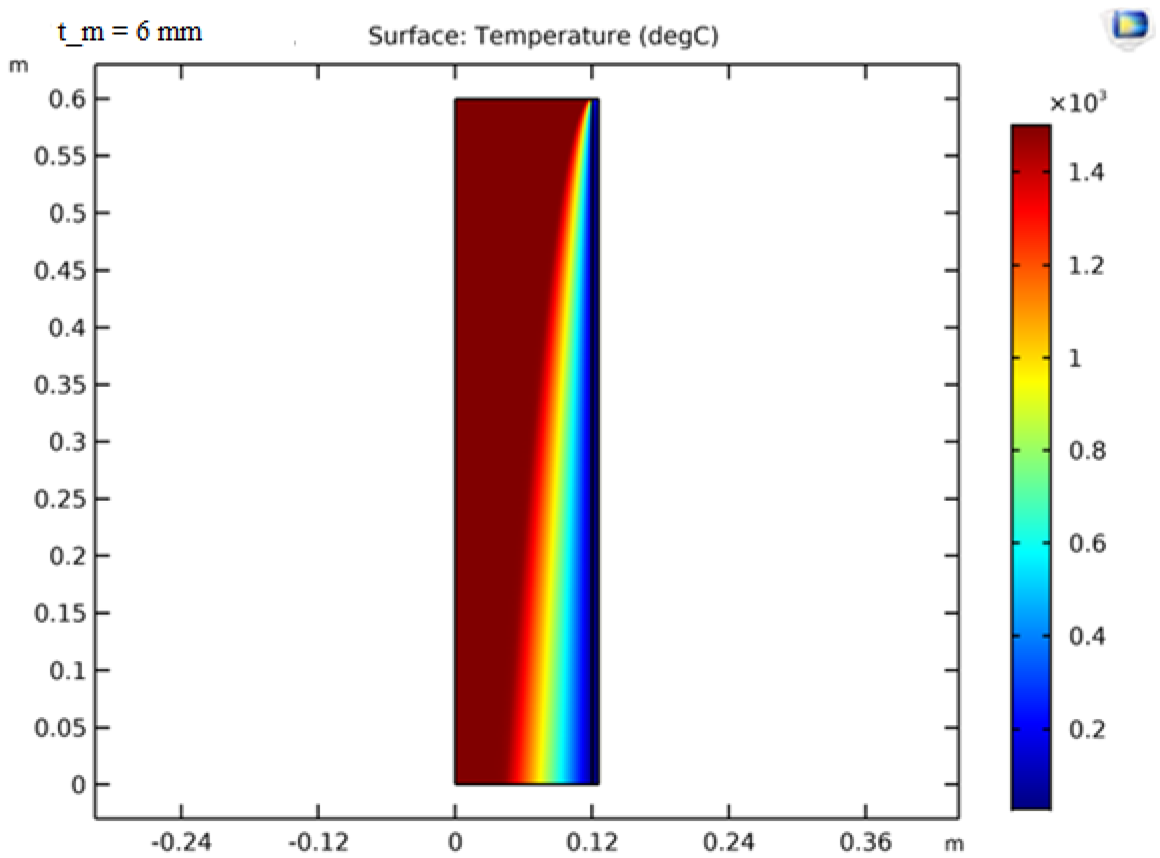
T_cast = 1600 °C, V_cast = 5 mm/s, t_**m = 10 mm**, K_liquid = 86 W/m.K, k_m = 398 W/m.K



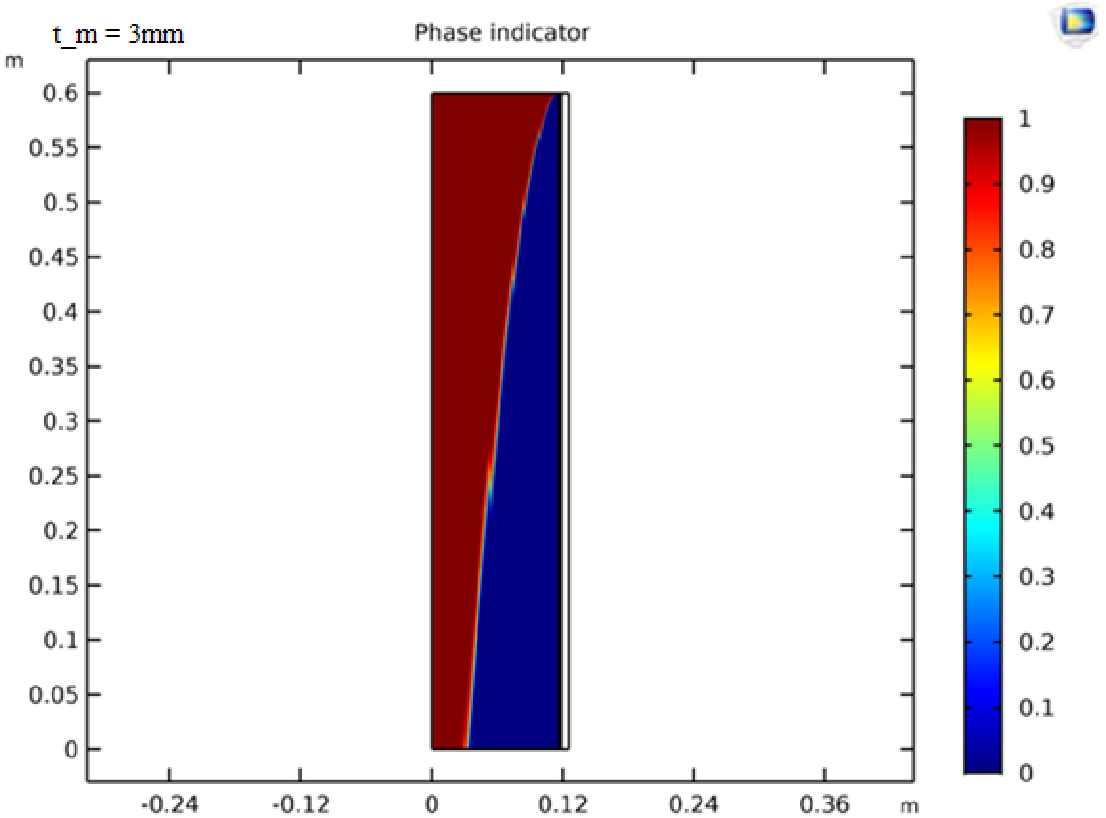


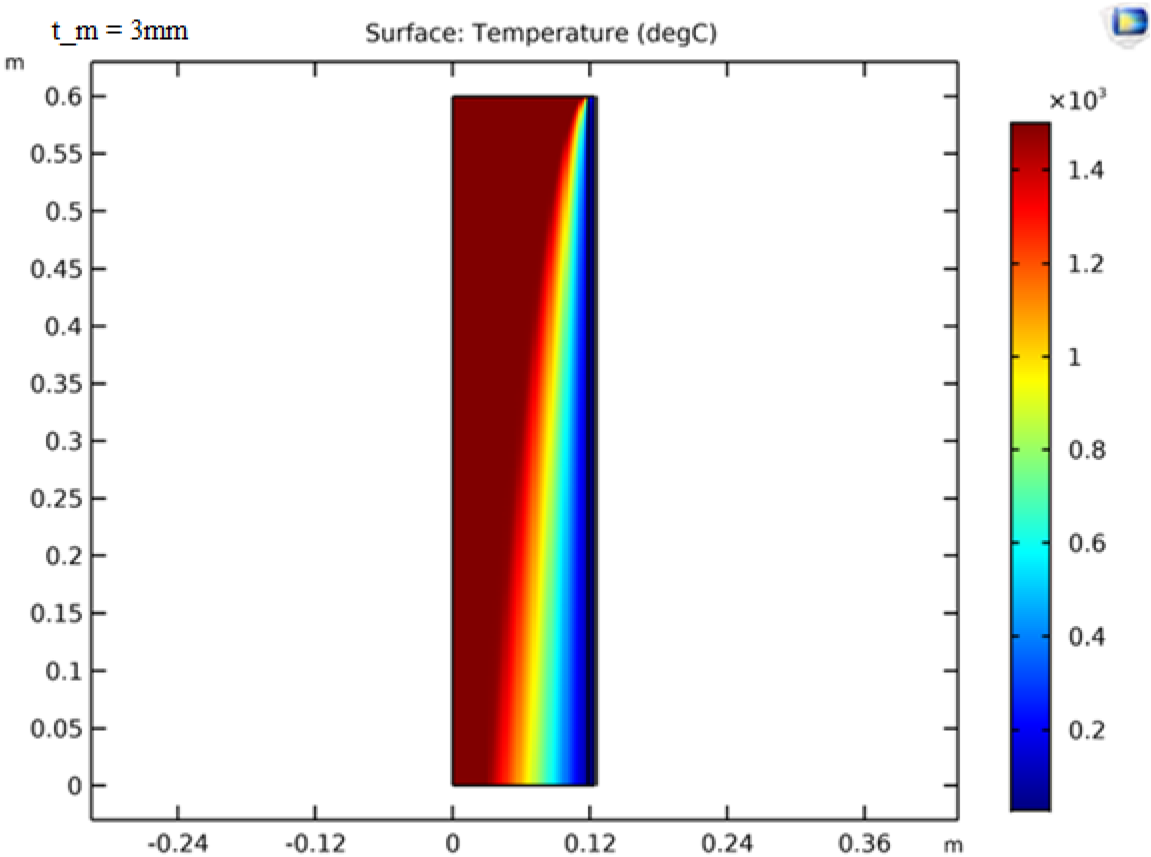
T_cast = 1600 °C, V_cast = 5 mm/s, **t_m = 6mm**, K_liquid = 86 W/m.K, k_m = 398 W/m.K





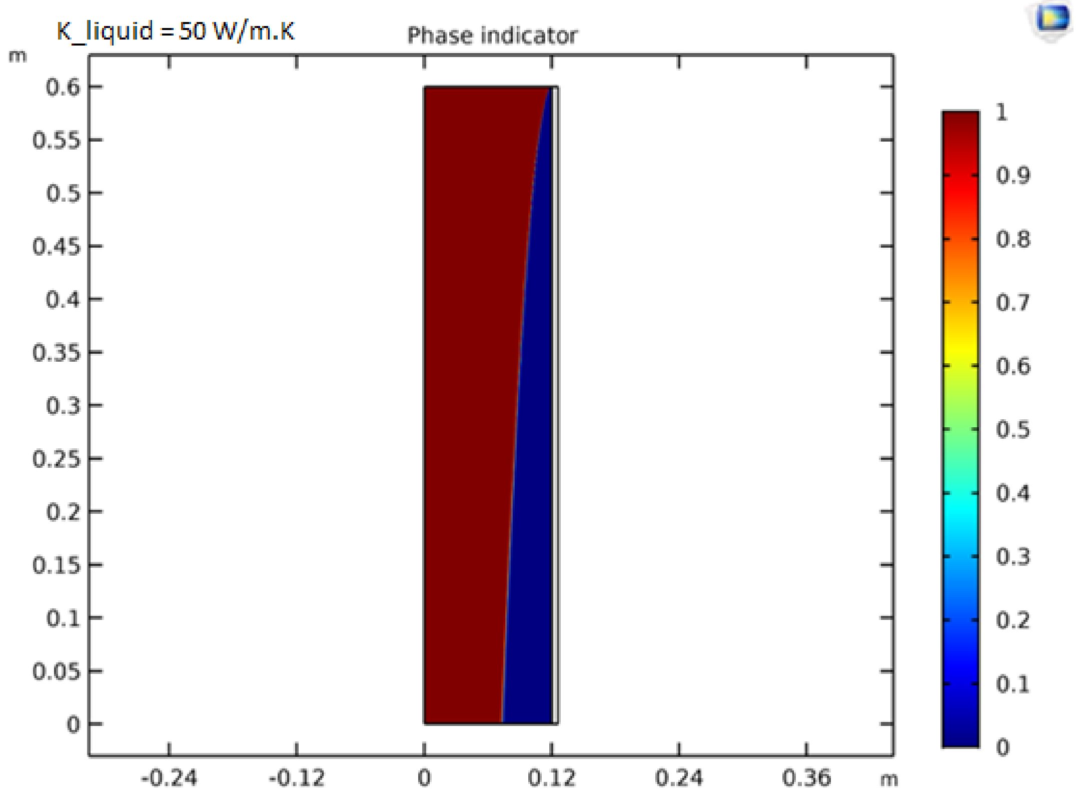
T_cast = 1600 °C, V_cast = 5 mm/s, **t_m = 3mm**, K_liquid = 86 W/m.K, k_m = 398 W/m.K

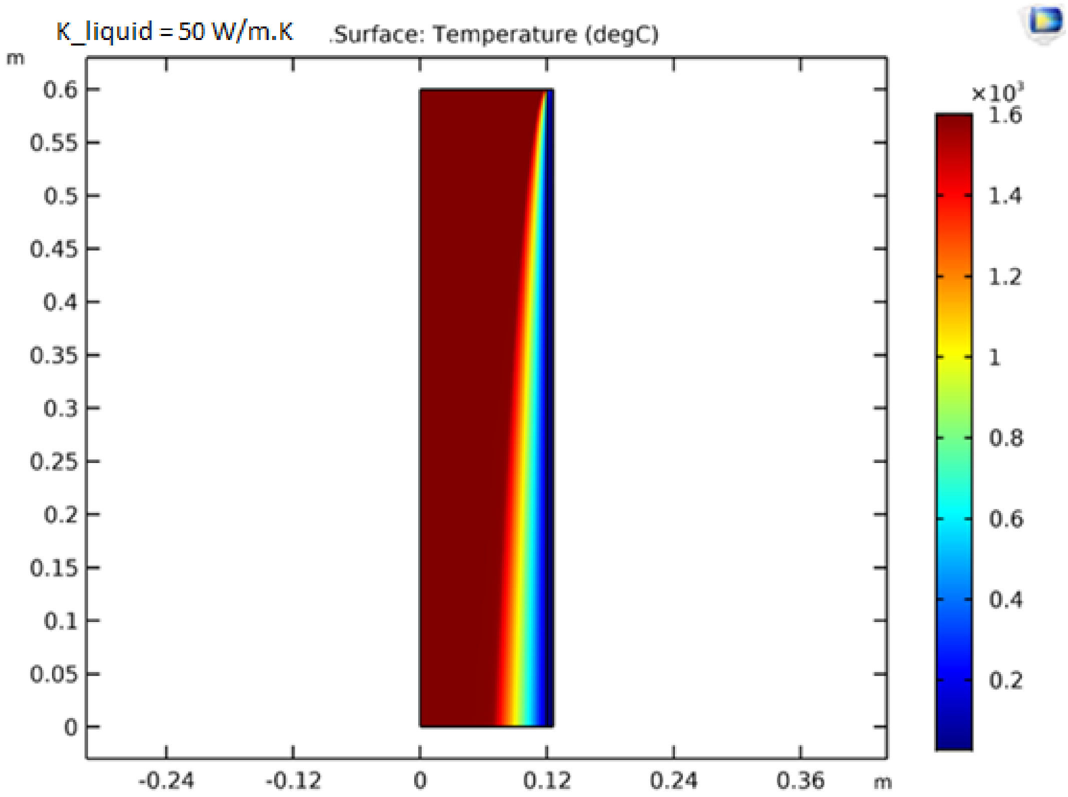




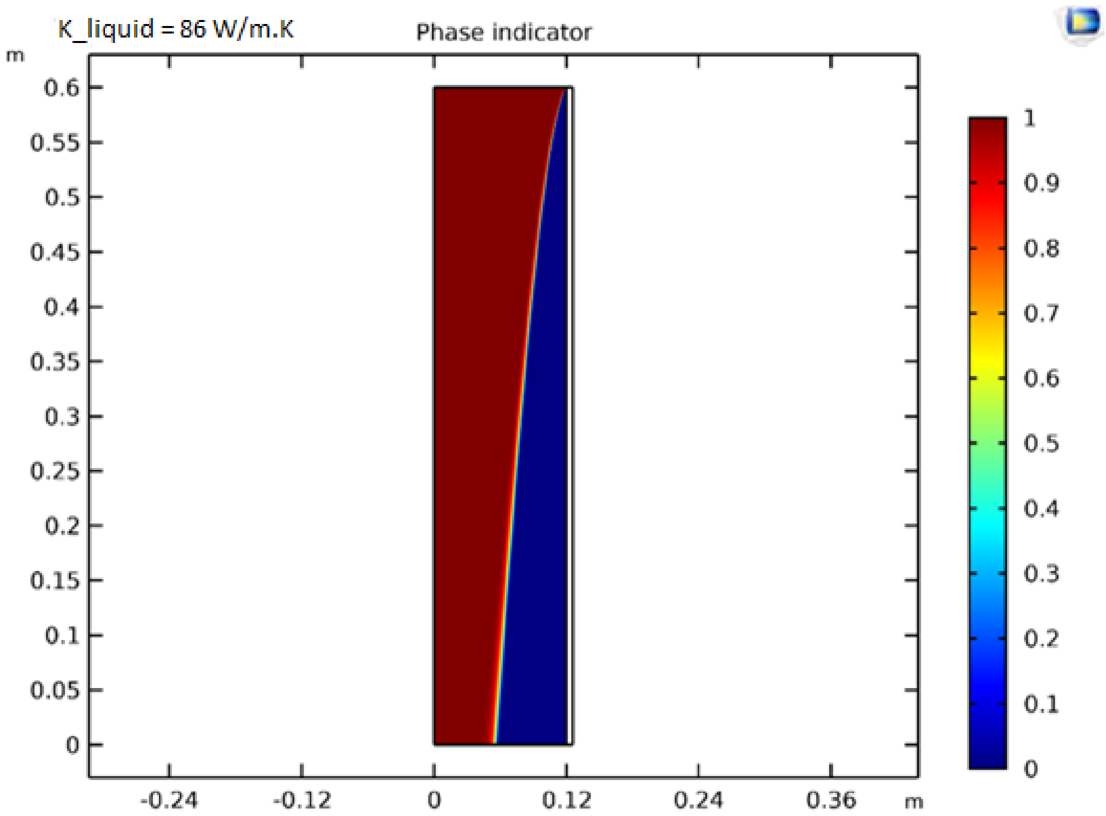
4.1.4 The Effect of Thermal Conductivity of The Molten:

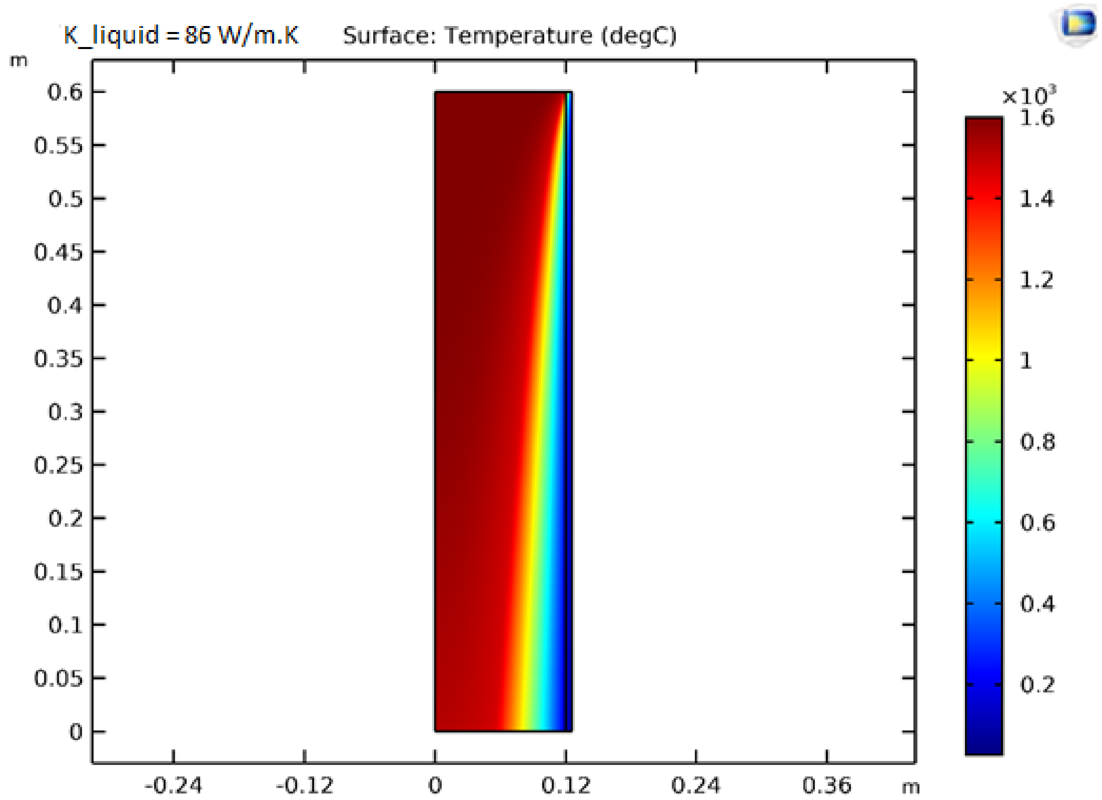
T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, **K_liquid = 50 W/m.K**,k_m = 398 W/m.K



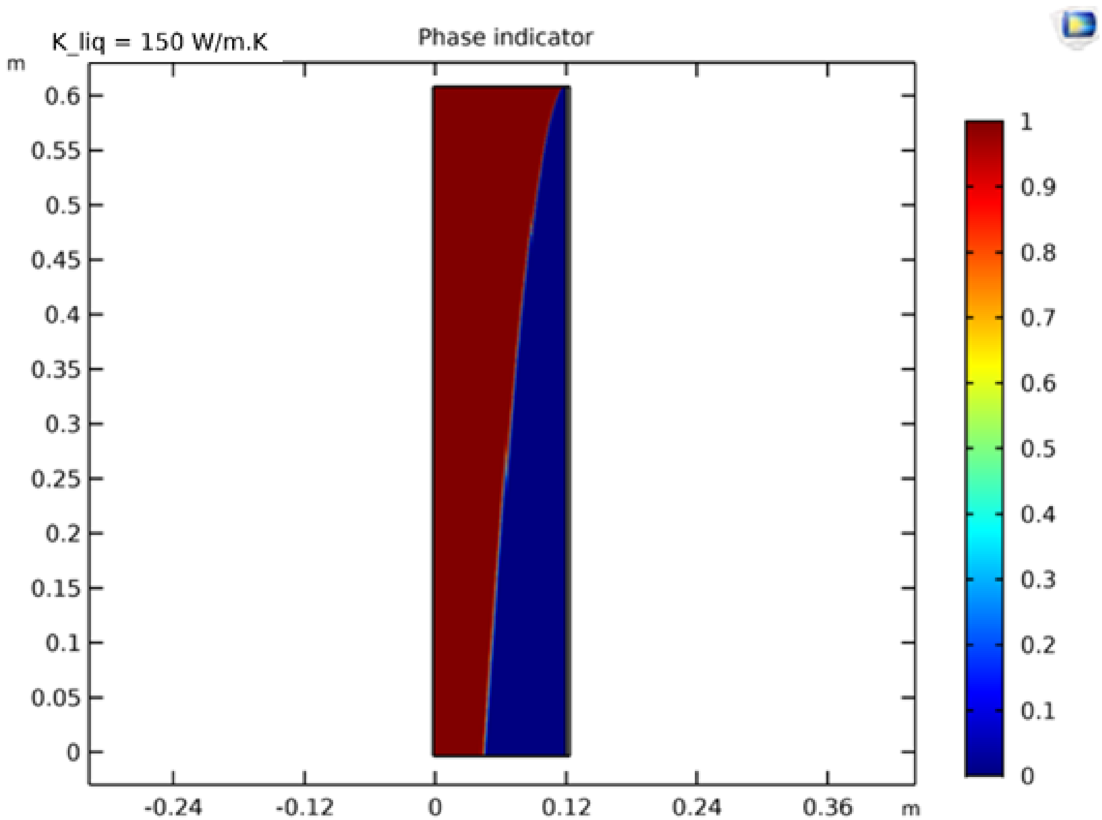


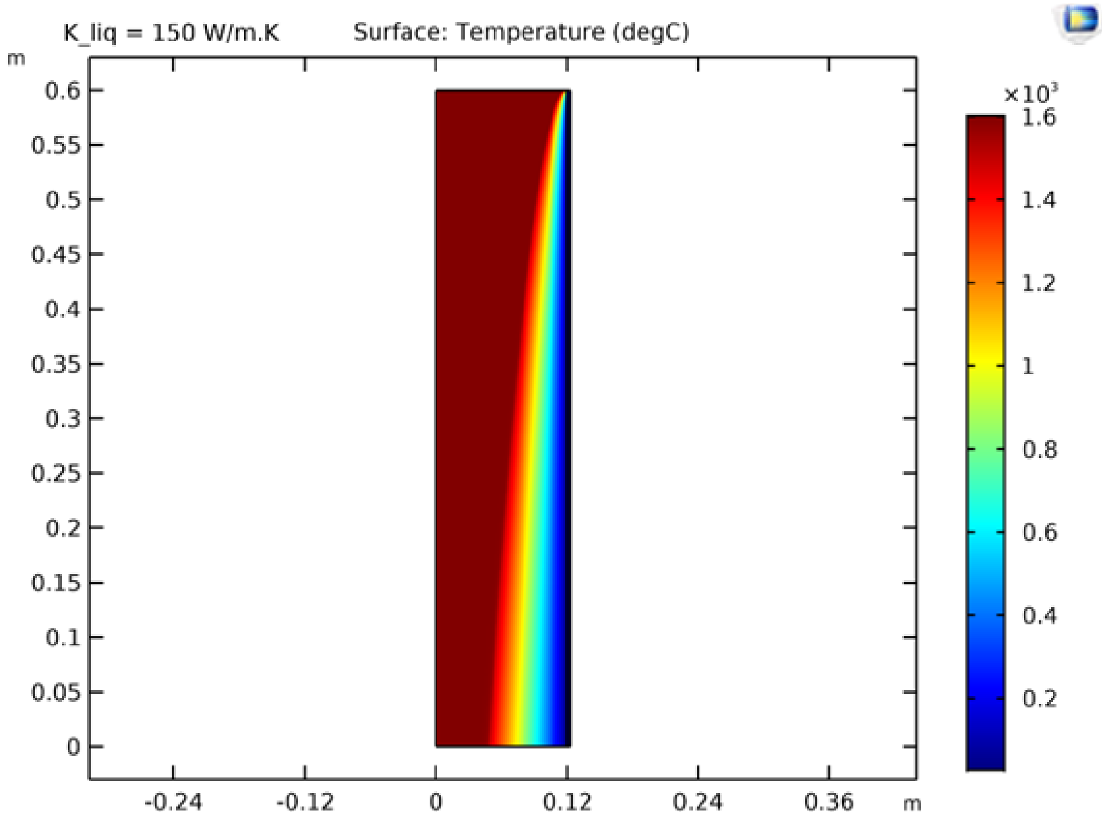
T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, **K_liquid = 86 W/m.K**, k_m = 398 W/m.K





T_cast = 1600 °C, V_cast = 5 mm/s, t_m = 6mm, **K_liquid = 150 W/m.K**, k_m = 398 W/m.K





4.2. Discussion:
Using the mathematical method described in the previous section, this research studied the sensitivity of the frozen layer thickness of molten to some of the parameters that affecting it, as the values of these parameters were changed in the calculation. The following table shows these parameters:

Table.1.5. Variables used in the calculation

Parameter	Values	Units
Temperature above Fusion (superheat)	1600 , 1550 , 1500	degre
Mold Thermal Conductivity	44 , 238 , 398	W/m.K
Mold Thickness	10 , 6 , 3	mm
Molten Thermal Conductivity	50 , 86 , 150	W/m.K

4.2.1. The Effect of Temperature above Fusion:
The temperature of over melt expresses the temperature that exceeds it at which the molten begins to freeze. During the casting of molten steel from the distributor to the casting molds, a heat loss of the molten occurs due to its direct exposure to air. Here it must be taken into consideration that the temperature above Fusion is sufficient to cover this heat loss during the casting process. In this study , the temperature above the melting point was changed according to the values (1600 ^{o}C , 1550^{o}C , 1500^{o}C) with other parameters such as mold thickness and thermal conductivity of the mold and molten fixed at values 6, 398, and 86, respectively . As shown in figure (5.1), it turns out the thickness of the frozen layer is affected by the value of the temperature above Fusion , so whenever the temperature decreases above Fusion, the thicker frozen layer. Figure 5.2 shows how sensitive the thickness of the freezing layer to the above-melting temperature.

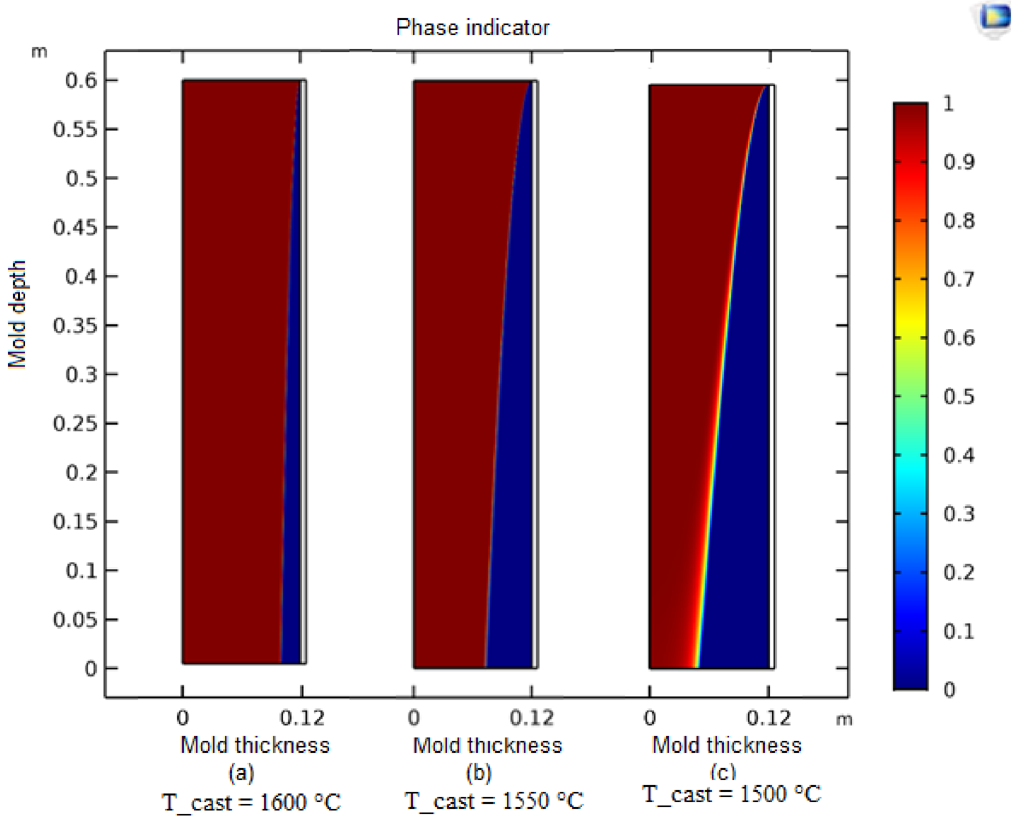


Figure. 5.1. Frozen layer thickness diagram for temperatures above Fusion.

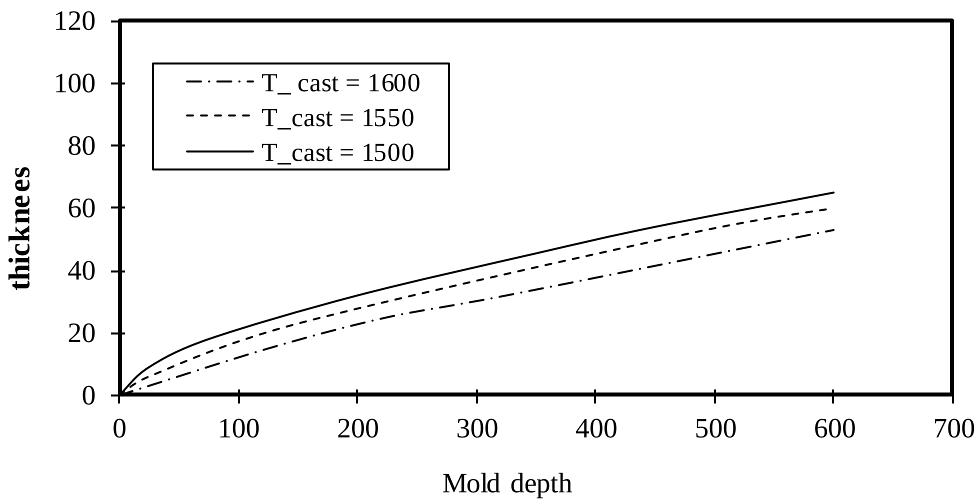


Figure. 5.2. The effect of temperatures above Fusion on Frozen layer thickness.

4.2.2. The Effect of Thermal Conductivity of the Casting Mold:

The thermal conductivity expresses the ability of the metal to conduct heat and is related to the interference of atoms in the metal when it is shaken as a result of high temperature. Three metals of the casting mold used in this study are structural steel, aluminum, and copper, where thermal conductivity changed from 44 , 238 , and 398 respectively and the stabilization of the above melting point, the thickness of the mold and the thermal conductivity of the molten at the values 1600,6, and 86 respectively. And as shown in the figures (5.3) and (5.4) that the effect the thermal conductivity of the mold on the thickness of the freezing layer is small compared to the effect of the above-melting point, where the thickness of the layer increases by a small amount as the thermal conductivity increases. It is worth nothing here that this does not mean that the thermal conductivity does not affect the thickness of the frozen layer, but due the small thickness of the mold, this effect is not significant . It is expected that this effect will be greater if the thickness of the mold is greater.

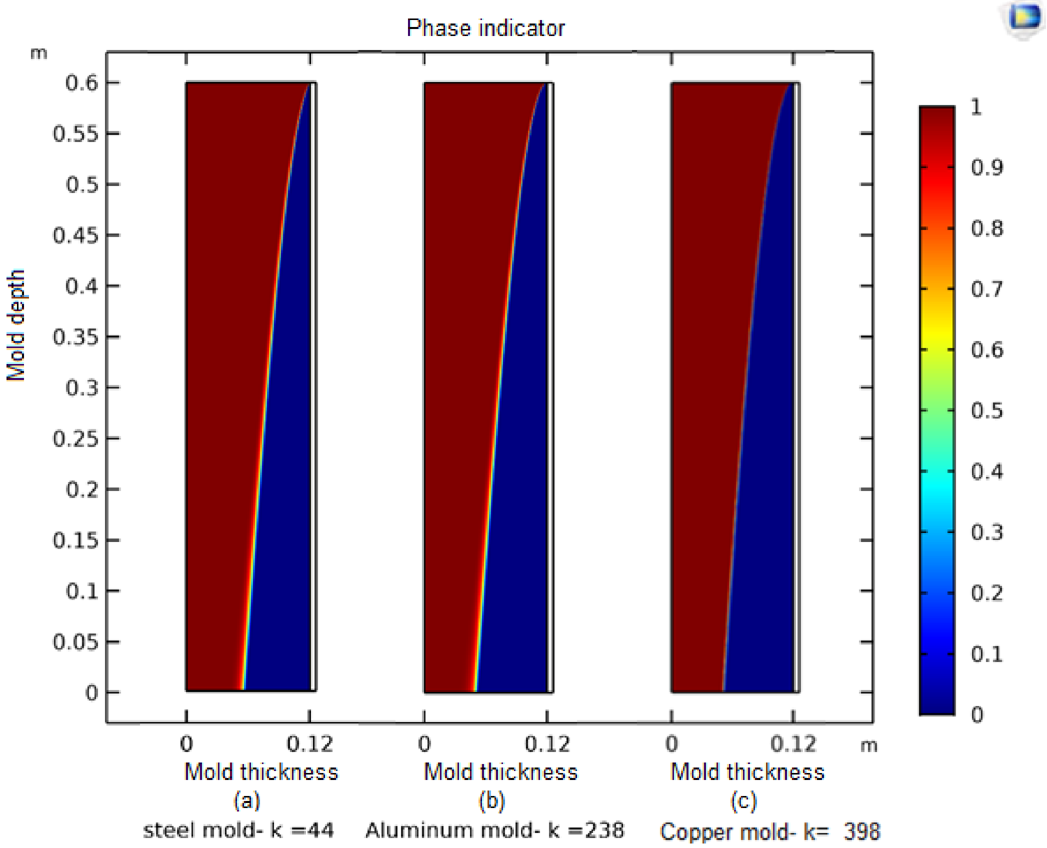


Figure. 5.3 Frozen layer thickness diagram when changing the thermal conductivity of casting mold.

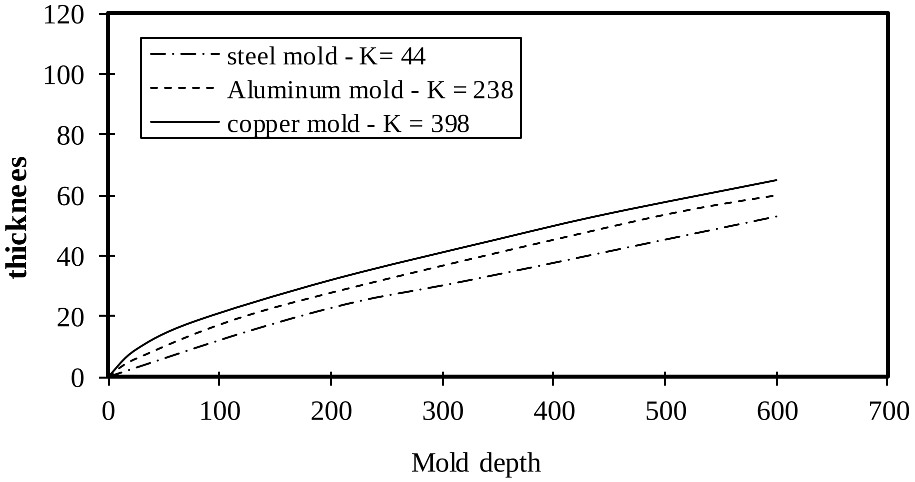


Figure 5.4: The effect of thermal conductivity of casting mold on frozen layer thickness.

4.2.3 Effect of Casting Mold Thickness:

It is well known that the rate of heat transfer is inversely proportional to the thickness of conductivity as mentioned in Fourier's first law

$$Q=k\frac{\Delta T}{-\Delta x}$$

Q represents heat flux (W / m.K), k is the thermal conductivity, Δx is the thickness of the thermal conductivity layer, and ΔT represents the temperature gradient. The thickness of a mold was changed in the calculation of the thickness of the frozen molten layer according to the values (10,6,3) with fixing the above-melting temperature and the thermal conductivity of the mold and the molten at the values (1600,398,86) respectively, as shown in Figures (5.5) and (5.6) the thickness of the casting mold has a clear effect on the thickness of the frozen layer. The higher the thickness of the mold, the lower the thickness of the frozen layer.

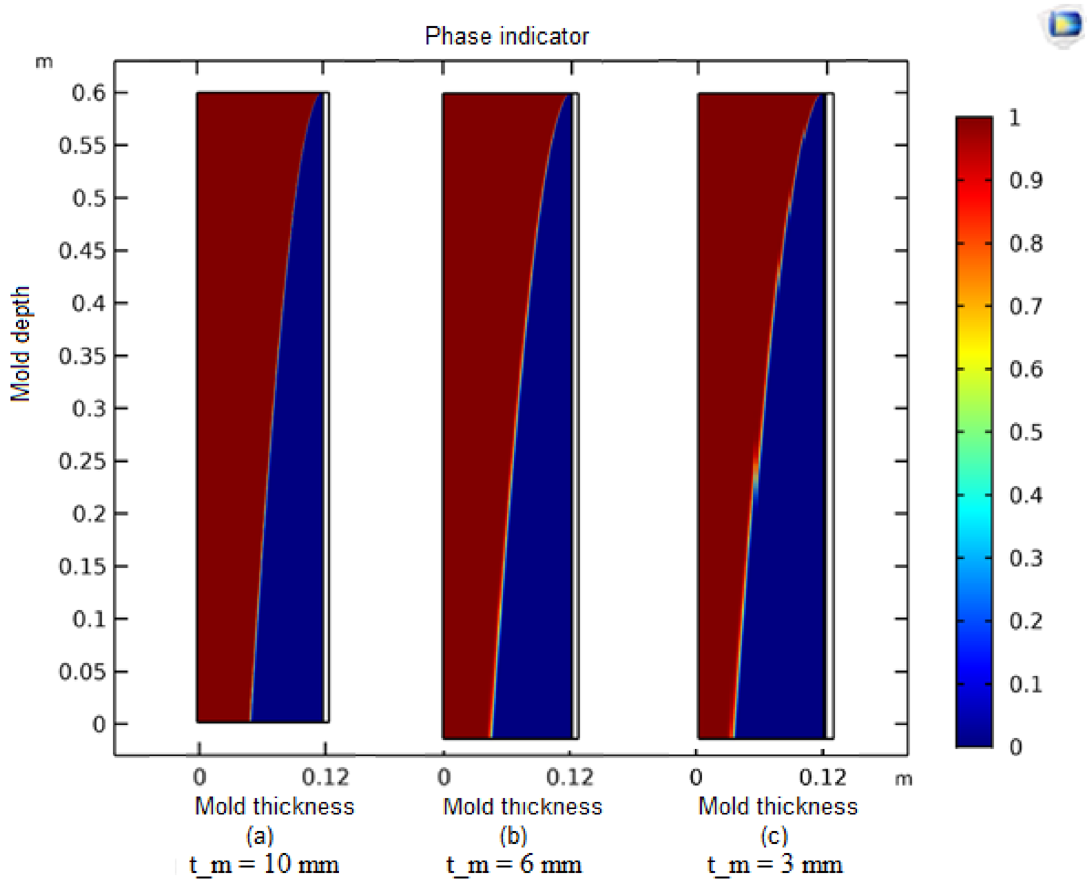


Figure 5.5 Frozen layer thickness diagram when changing the casting mold thickness.

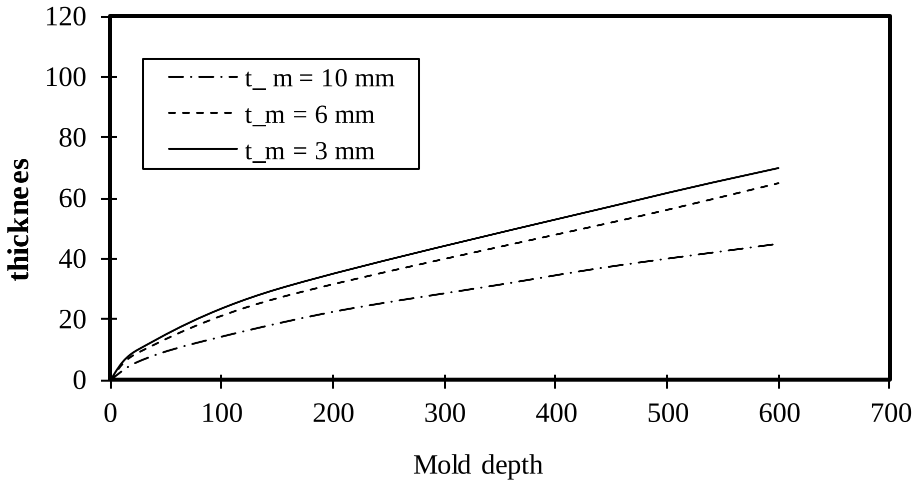


Figure 5.6The effect of casting mold thickness on Frozen layer thickness.

4.2.4 The Effect of Molten Thermal Conductivity:

The thermal conductivity of steel melt expresses the ability of the melt to allow heat to move through it as the conductivity of steel depends on the amount of alloy elements added to it for the purpose of improving mechanical properties. In this study, the thermal conductivity was changed(W / m-K) for molten steel according to the values (50,86,150) and fixation of the above fusion, mold thickness and thermal conductivity of the mold at values (1600,6,398) respectively Figures (5.7) and (5.8) show how sensitive the thickness of the frozen layer to the conductivity of molten steel, it is clear from these figures that the thickness of the frozen layer is clearly affected by the value of the molten conductivity, as its thickness increases with the increase of this conductivity.

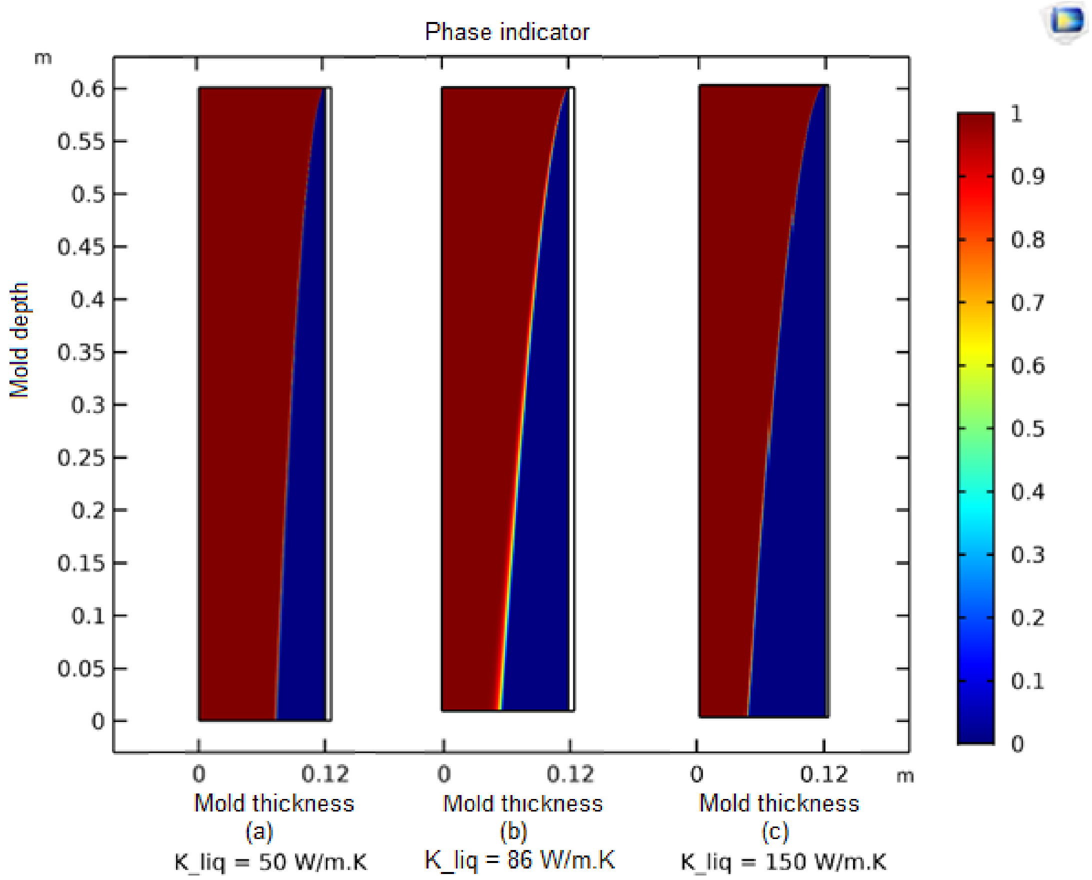


Figure 5.7 Frozen layer thickness diagram when changing the thermal conductivity of molten steel.

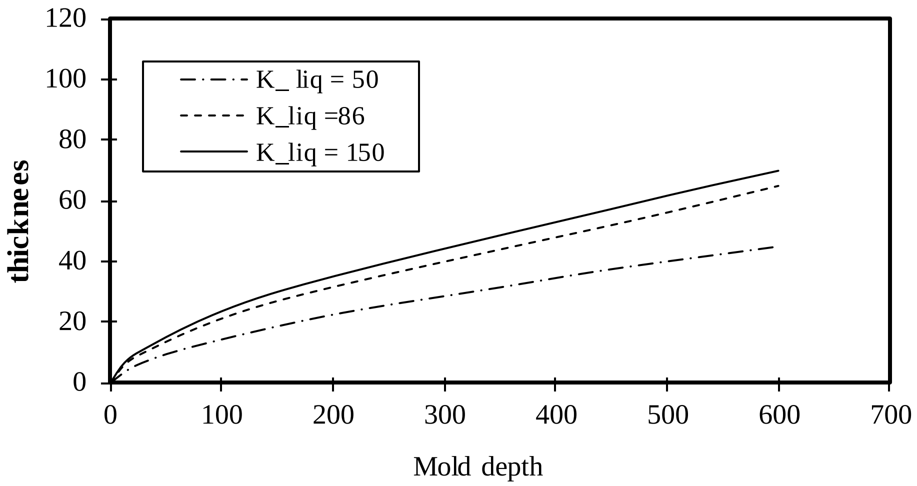


Figure. 5.4 The effect of thermal conductivity of molten steel on Frozen layer thickness.

In general, it is clear from these results that the parameters that have the greatest effect on the thickness of frozen layer are the temperature above melting and the thermal conductivity of the steel melt.

5.1. Conclusions:

Through the simulation results conducted on the molten steel casting process, which consisted in looking at the sensitivity of the frozen layer thickness to some parameters related to the casting process, the following conclusions were reached.

1- The above melting temperature has a clear effect on the thickness of the frozen layer

2- The thermal conductivity of the cooling mold does not have much effect on the thickness of the frozen layer due to the small thickness of the casting mold

3- The thickness of the cooling mold has a clear effect on the thickness of the frozen layer

4- The thermal conductivity of the molten steel has a clear effect on the thickness of the frozen layer

5.2. Recommendations:

Based on the conclusions reached in this research, the following recommendations can be drawn

1- Indirect cooling of steel melt inside the cooling system. The above melting temperature of the steel melt must be appropriate, as well as the thickness of the cooling system mold is appropriate until a thickness suitable for the frozen layer of the direct drawing and cooling process is obtained.

2- The quantity of alloyed elements added to the molten steel must be determined in order to reach a suitable thermal conductivity to obtain a thickness suitable for the frozen layer of direct drawing and cooling process

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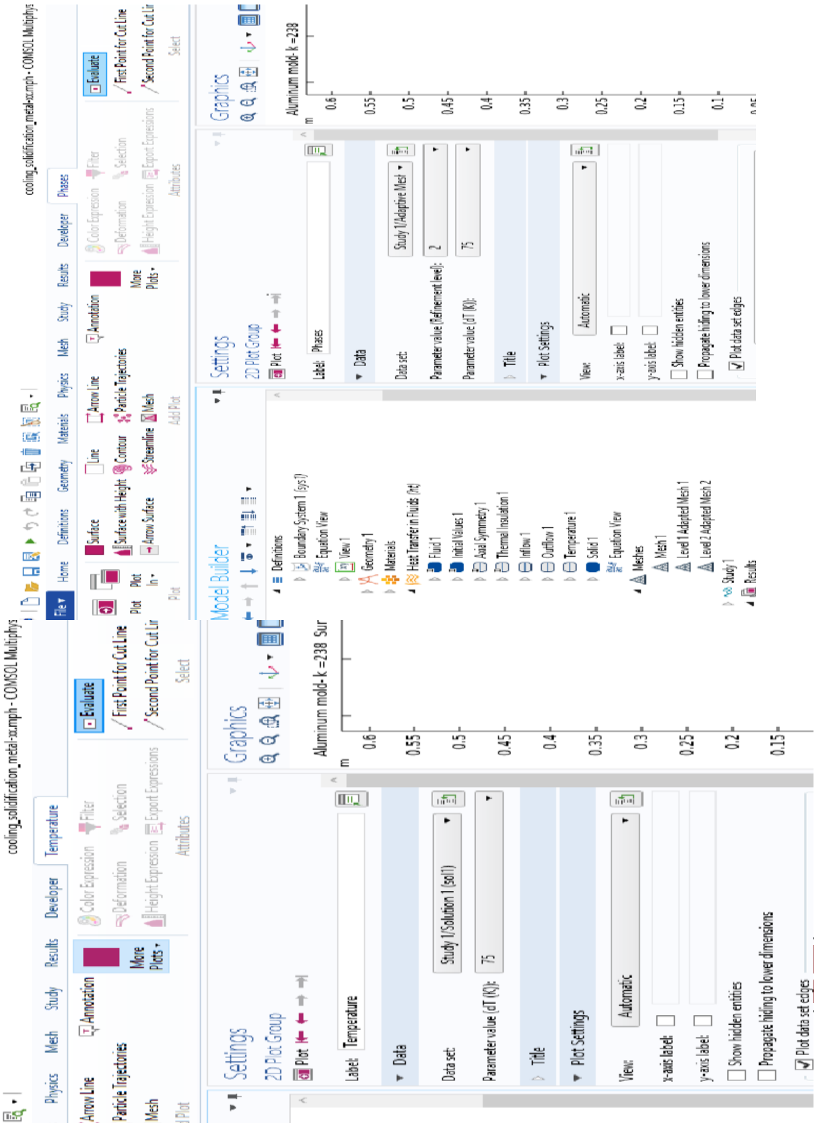
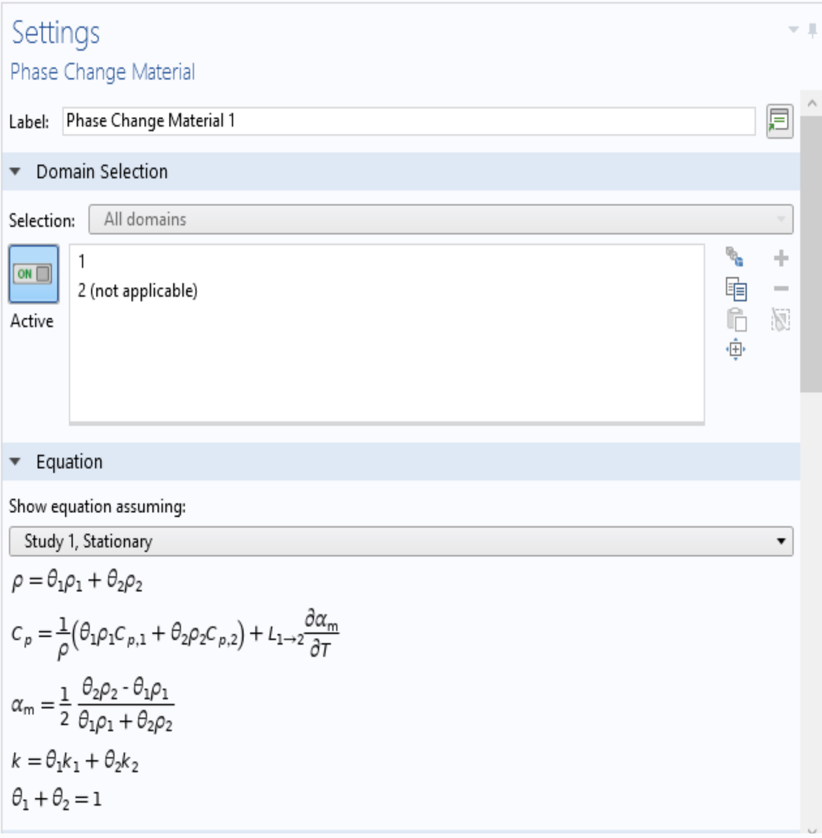
APPENDIX (A)
Sample of Calculation




Settings
Phase Change Material
Label: Phase Change Material 1
Domain Selection
Selection: All domains
1
2 (not applicable)
Active
Equation
Show equation assuming:
Study 1, Stationary
$\rho = \theta_1\rho_1 + \theta_2\rho_2$
$C_p = \frac{1}{\rho}(\theta_1\rho_1 C_{p,1} + \theta_2\rho_2 C_{p,2}) + L_{1\to 2}\frac{\partial \alpha_m}{\partial T}$
$\alpha_m = \frac{1}{2}\frac{\theta_2\rho_2 - \theta_1\rho_1}{\theta_1\rho_1 + \theta_2\rho_2}$
$k = \theta_1 k_1 + \theta_2 k_2$
$\theta_1 + \theta_2 = 1$

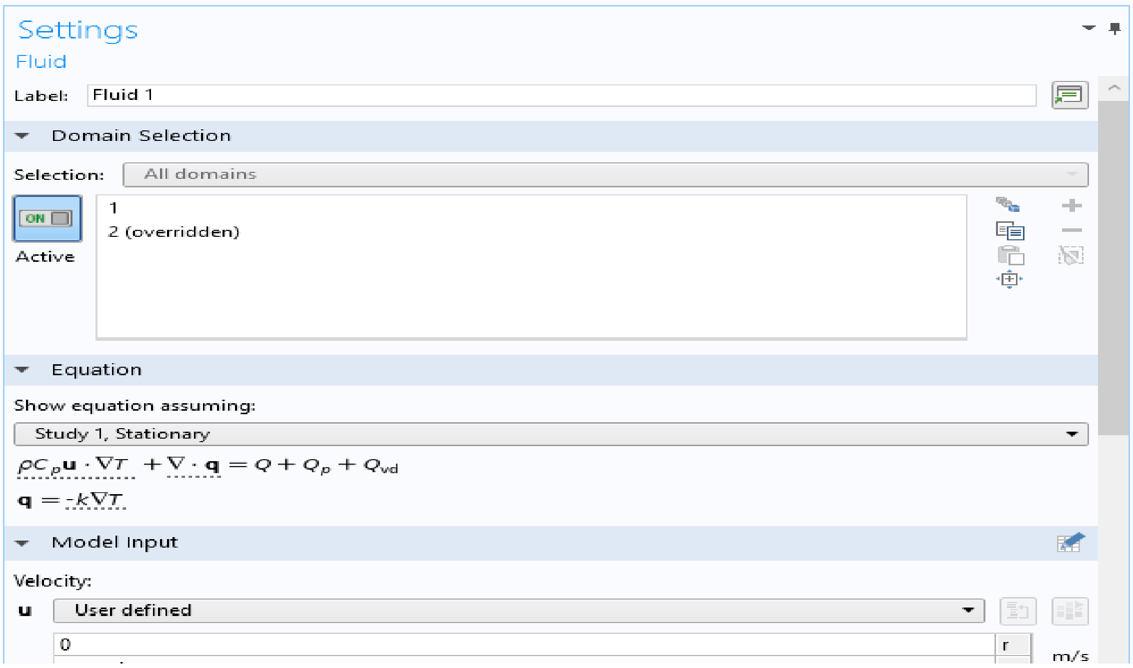

Settings
Fluid
Label: Fluid 1
Domain Selection
Selection: All domains
1
2 (overridden)
Active
Equation
Show equation assuming:
Study 1, Stationary
$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_p + Q_{vd}$
$\mathbf{q} = -k\nabla T$
Model Input
Velocity:
u
User defined
0
m/s

Table (A.1) Results of frozen layer thickness when changing the Temperature above Fusion.

T=1600°C		T=1550°C		T=1500°C	
Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness
0	0	0	0	0	0
25	4	25	6	25	10
225	11	150	20	200	36
325	14	480	36	450	60
600	25	600	42	600	72

Table (A.2) Results of Frozen layer thickness when changing the Thermal Conductivity of the Mold.

Steel (K=44)		Aluminum (K=238)		Copper (K=398)	
Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness
0	0	0	0	0	0
125	15	25	6	25	9
225	25	150	23	200	32
325	32	480	52	450	54
600	53	600	60	600	65

Table (A.3) Results of Frozen layer thickness when changing the Casting Mold Thickness.

T_m=10mm		T_m=6mm		T_m=3mm	
Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness
0	0	0	0	0	0
25	8	25	10	25	12
200	30	150	30	200	42
450	50	480	60	450	70
600	60	600	72	600	84

Table (A.4) Results of Frozen layer thickness when changing the Molten Thermal Conductivity.

K_liq=50		K_liq=86		K_liq=150	
Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness	Mold depth	Frozen layer thickness
0	0	0	0	0	0
25	6	25	9	25	10
200	22.5	150	27	150	30
450	37.5	480	54.5	480	60
600	45	600	65	600	70