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A 2-D Numerical Solution of Temperature Distribution, Solidification Time and Thickness in Continuous Slab Casting

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Abstract

Continuous casting is the process of using continuous casting machines and furnaces in casting metals into endless lengths of strips or slabs which can be further shaped into other suitable products. The process may sound simple but it is a complex metallurgical process requiring closely coordinated analyses of the relevant casting parameters. In this study, the Galerkin Finite Element method has been employed in the numerical analyses of temperature distribution, solidification time and solidification thickness in continuous casting. From the analysis, in order to prevent the mould from collapsing due to sudden change in temperature, the mould was preheated to a temperature of 320^{0}C while the pouring temperature of the liquid cast was 1546^{o}C. In the solidifying steel shell it was observed that there was a linear increase from 0.0005m to 0.0155m in the solidification of the liquid cast along the shell with time since there was continuous cooling with water. The pouring temperature of the liquid cast was varied between 1488^{0}C and 1546^{0}C and using this range of pouring temperatures, the liquid cast completely solidified between 23.6 min and 28.0 min. The results obtained from the analysis were validated with the work from literature using the 2-D Time approximation model.

1. Introduction

[1] developed a steady state, two-dimensional mathematical model for continuous billet casting operations. The governing equations of fluid flow and heat transfer together with their appropriate set of boundary conditions were derived and solved numerically via a control volume based implicit finite difference procedure. The effect of various assumptions and procedures applied to modelling of turbulence phenomena, thermal buoyancy, flow through the mushy zone, and free surface conditions on the sensitivity of the computed results were investigated. Considering all the models, the model for heat and fluid flow phenomena in the mushy region was found to have relatively more effect on the predicted results. Furthermore, a set of three different billet casting operations were simulated mathematically and direct comparisons were made between predicted and observed solidified shell profiles. [2] carried out an analysis of the effect of pouring temperature in steel slabs on the continuous casting processes and further investigated the Relationships between pouring temperature (P_T) and center macro-segregation. They performed experiments using Photomicrographs of specimen taken from transverse sections of steel slabs. From their investigations it showed that macro-segregation is strongly affected by pouring temperature (P_T). It was also shown from their research that for considered steels, the pouring temperature (P_T) influences the position of the columnar to equiaxed transition (CET). Experimental results showed that the end of the columnar region is abbreviated when lower pouring temperatures was used in continuous casting process. It was further observed that as the pouring temperature (P_T) increase in

continuous casting process, the secondary dendritic arm spacing (λ_2) increase, i.e., the dendritic morphology became coarsen.

In 2011 [3] presented a mathematical and numerical simulation model of the growth of the solid metal phase within a continuous cast slab. They obtained velocity fields by solving the momentum equations and the continuity equations; furthermore, the thermal fields were calculated using the conduction equation with the convection term. They took into consideration the changes of thermophysical parameters which depend on the temperature and the solid phase volume fractions in the mushy zone. This formulation of the problem is called a complex model in contrast to the simplified model in which the conduction equation is solved only. The problem was solved by the finite element method. A numerical simulation of the cast slab solidification process was made for different cases of continuous casting mould pouring by molten metal. The influences of cases of the continuous casting mould pouring on the velocity fields in liquid phase and the solid phase growth kinetics of the cast slab were estimated.

[4] stipulated a heat transfer and solidification model which described the continuous casting of steel slabs. The model was established on the basis of the technical conditions of the slab caster in the continuous casting unit of Mobarakeh steel company in Iran. They used the finite-volume method solve the governing equation which involves a two dimensional (2-D) transient equation. The boundary conditions of the mould, water spray cooling and air cooling regions were defined. The mathematical model was used to predict the shell thickness temperature distribution in the mould and shell, and the interfacial gap between shell and mould.

[5] in his work investigated the influence of steel grade, mould powder and casting conditions on process stability by including heat and mass transfer through liquid steel, slag film layers and solidifying shell. The research addressed the application of a numerical model capable of coupling the fluid flow, heat transfer and solidification developed by Swerea MEFOS; based on the commercial CFD code FLUENT v12. The Volume of Fluid (VOF) method, which is an interface tracking techniques was used in the analysis, Pooria went further to describe the implementation of the model to analyse several steel and mould powder combinations which led to detection of a combination suffering from quality problems. The results obtained from the analysis showed the importance of steel pouring temperature, mould powder break temperature and also solidification range on the lubrication efficiency and shell formation.

The solidification rate constant substantially depends on three factors; the dimensions of the cast strand cross-section, the temperature of steel superheating over the liquidus temperature, and the chemical composition of the steel cast and the cooling intensity [6]. [7] presented a value for the solidification rate constant for low carbon steel to be 23.4 mm/min$^{0.5}$.

This research sort to look at the temperature distribution, the solidification time and thickness in the various zones using the Galerkin Finite Element method on Grade 1 steel (Low carbon steel which contains 0.16% of carbon and some other elements) which will significantly increase the accuracy of the results obtained in continuous casting using the transient state of the heat conduction equation.

2.0 Methodology

In the development of the weak form, it is assumed that the domain is rectangular and we develop the finite element equation of Equation (1) over the domain.

Using the heat transfer equation with necessary boundary conditions for a 2-D $x-y$ plane we have [8]:

$$C\rho\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial T}{\partial y}\right) \tag{1}$$

Where k_x and k_y are the thermal conductivity coefficient in the x and y directions, respectively

Equation (1) is weaken by introducing a weight function *W* which is shown in Equation (2) known as the weak form.

$$0 = -C\rho\int_A W\frac{\partial T}{\partial t}dA - k\left(W\frac{\partial T}{\partial x}\bigg|_A + W\frac{\partial T}{\partial y}\bigg|_A\right) + k\int_A\left(\frac{\partial W}{\partial x}\frac{\partial T}{\partial x} + \frac{\partial W}{\partial y}\frac{\partial T}{\partial y}\right)dA \quad (2)$$

The weak form requires that the approximation chosen for *T* be at least linear in both the x and y direction so that there are no terms in it that are identically zero. Since the primary variable is simply the function itself, the Lagrange family of interpolation function is admissible [9].

Let $q = \left(W\frac{\partial T}{\partial x}\bigg|_A + W\frac{\partial T}{\partial y}\bigg|_A\right)$ and (3)

$$W = \psi_i^e(x, y) \text{ And } T = \sum_1^n T_j^e \psi_j(x, y) \quad (4)$$

The interpolation function is introduced into the weak form to enable us derive the finite element model for the 2-D analysis. Following the Garlerkin finite element method procedures the finite element based model equation (1) is simplified to Equation (5) referred to as the developed finite element based model [8] for the 2-D heat transfer equation in continuous slab casting.

$$k\left[K^e\right]\left\{T_j\right\} + C\rho\left[M^e\right]\left\{\dot{T}_j\right\} = kq \quad (5)$$

$$\left[K^e\right] = \int_{x_1}^{x_2}\int_{y_1}^{y_2}\left(\frac{\partial\psi_i^e}{\partial x}\frac{\partial\psi_j}{\partial x} + \frac{\partial\psi_i^e}{\partial y}\frac{\partial\psi_j}{\partial y}\right)dxdy \quad (6)$$

$$\left[M^e\right] = \int_{x_1}^{x_2}\int_{y_1}^{y_2}\psi_i^e\psi_j^e\,dxdy \quad (7)$$

$\left[K^e\right]$ is the thermal conductivity matrix and $\left[M^e\right]$ is the enthalpy matrix

The Langrange interpolation function for a quadratic element used in the analysis is shown in Equations (8) to Equation (11).

$$\psi_1 = \left(1 - \frac{x}{X}\right)\left(1 - \frac{y}{Y}\right) \quad (8)$$

$$\psi_2 = \frac{x}{X}\left(1 - \frac{y}{Y}\right) \quad (9)$$

$$\psi_3 = \frac{x}{X}\frac{y}{Y} \quad (10)$$

$$\psi_4 = \frac{y}{Y}\left(1 - \frac{x}{X}\right) \quad (11)$$

Time approximation equation for conductive heat transfer model is derived by solving the finite element based model using the α family of interpolation in which a weighted average of the time derivative of dependent variable is approximated to two consecutive time steps by linear interpolation of values of the variables [10]. Crank Nicholson Scheme was used where the α value is 0.5 [8]. Equation (12) is obtained and known as the time approximation function for the 2-D heat transfer in continuous casting.

$$\{T_j\}_1 = \left[C\rho\left[M_{ij}^e\right] + k\frac{\Delta t_1}{2}\left[K_{ij}^e\right]\right]^{-1}\left[C\rho\left[\left[M_{ij}^e\right] - k\frac{\Delta t_1}{2}\left[K_{ij}^e\right]\right]\{T_j\}_0 + \frac{\Delta t_{s+1}}{2}\{q_i^e\}_{s+1}\right] \tag{12}$$

3.0 Results and discussion

The design parameters, the boundary conditions, the values of the thermal conductivity matrix, and values of the enthalpy matrix were computed into the time approximation Equations for the 2-D analysis which generates the temperature distribution in the continuous casting process. Table 1 shows the thermo physical properties of Grade 1 steel (0.16% carbon)

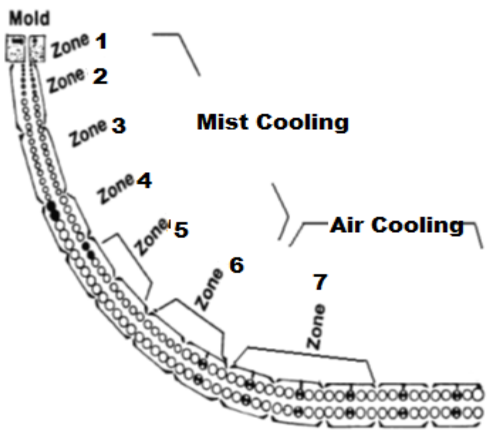

Figure 1: Secondary cooling of the various zones

Table 1: Thermo physical properties of casting material

Thermo Physical Properties	Grade l Steel
$K_d\left(cal/cm\sec^0 C\right)$ at 0^0C	0.025
$\rho\left(gr/cm^3\right)$	7.3
$\rho\left(cal/gm^\circ C\right)$	0.118
$T_s\left(^0C\right)$	1494
$T_l\left(^0C\right)$	1546
$T_f\left(^0C\right)$	158
$\Delta H\left(cal/gr\right)$	60
Melting Heat (J/kg)	244000

Figure 1 shows the various zones analyzed in the continuous casting process, the temperature distribution and solidification thickness and time was determined using the Fourier heat transfer equation applying the necessary boundary conditions for the various zones from zone 1 to zone 7. Table 2 shows the design parameters of the copper mould used in the analysis.

Table 2: Design and operating parameters used in analysis of the Mould [4]

Preheat Temperature (°C)	320
Mould plate thickness (m x m)	0.043x0.030
Mould length (m)	0.704
Working Mould length (m)	0.659
Mould Copper plate width (m x m)	2.220x0.215
Mould Conductivity k_{mould} (W/mK)	315
Scale thickness on the surface of mould cold surface (m)	0.00001
Mould Powder Conductivity k_{slag} (W/mK)	1.27
Mould powder density $\rho_{slag}\left(kg/m^3\right)$	0.650
Mould Powder Consumption rate M_{slag} (kg/ton steel)	0.8
Copper Mould melting point (°C)	1084

Using Equation (12) the heat flow in the solidifying shell was analysed, this is so because there is bound to be cooling in the x-y direction (2-D) [11], since the 1-D state cannot be used effectively to analyse this region. Figure 2 shows the variation of growth of the solid shell thickness on the ingot.

It further shows that there is a linear increase of 0.0005m to 0.0155m in the solidification of the liquid cast along the shell with time since there is continuous cooling with water.

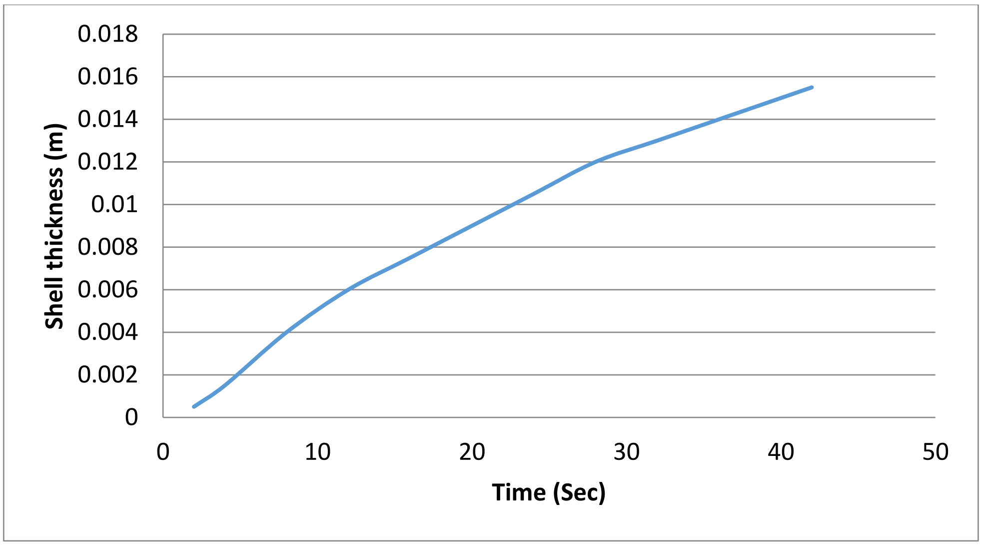

Figure 2: A graph of shell thickness with time (This work)

Figure 3 shows a graph of solidification time against pouring temperature. It was observed that the time for complete solidification increases with increased pouring temperature of molten metal. The pouring temperature was taken between 1488.234^{0}C and 1546^{0}C. The variation of solidification time as a function of initial pouring temperature given that the mould was preheated to a temperature of 320 ^{0}C. In Figure 3, using the range of pouring temperatures, the liquid cast completely solidifies between 23.6 min and 28 min.

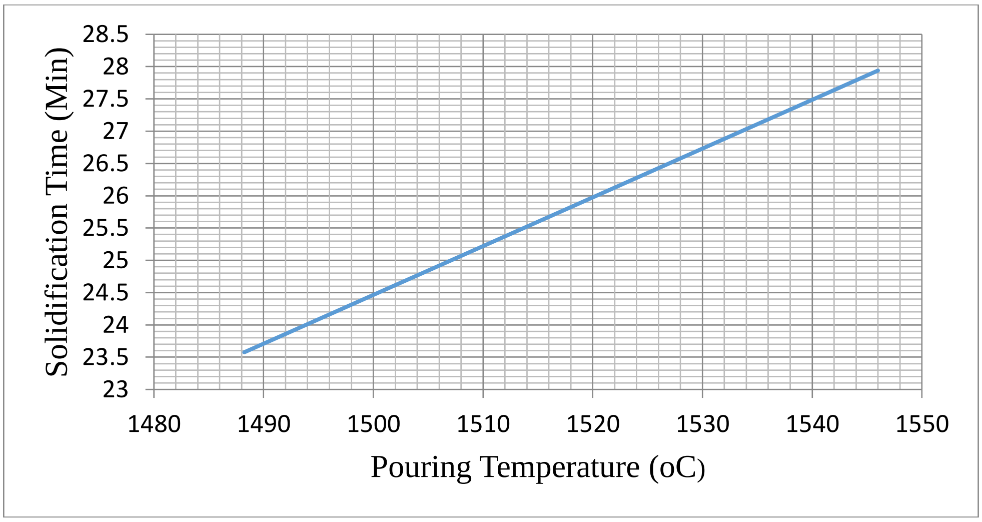

Figure 3: A graph of Solidification time against Pouring Temperature

3.1 Analysing the various zones

Using the parameters presented in Table 2 and the 2-D heat transfer equation, the Temperature distribution was analysed for the various zones in the continuous casting set up. For the purpose of presentation, the zone immediately after the mould is zone 2 and the temperature distribution is shown using the contour plot and surface plot in Figure 4 and Figure 5 respectively.

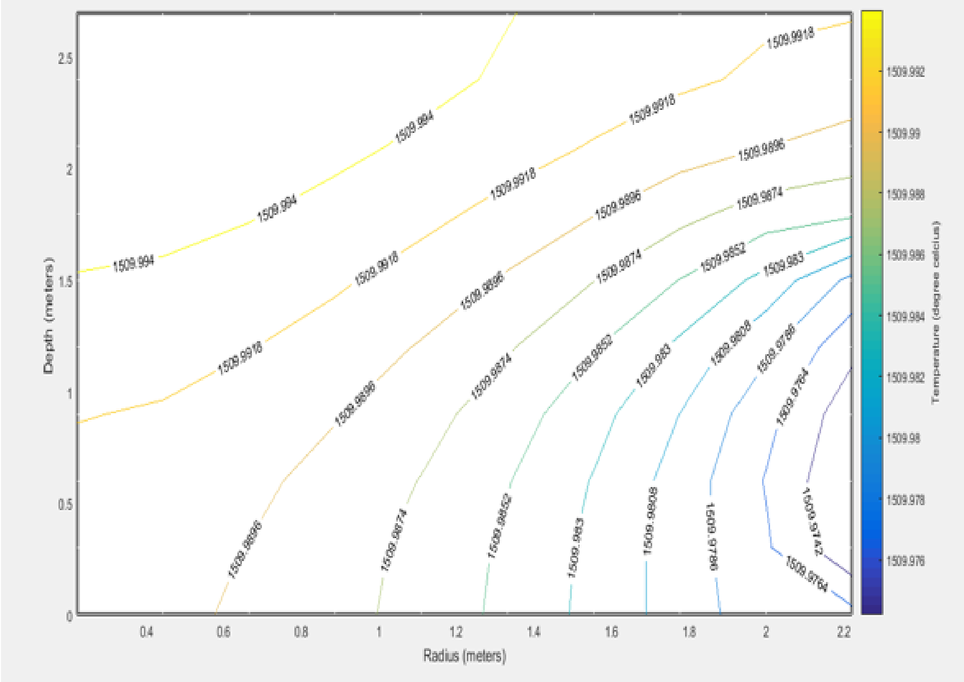

Figure 4: Prediction of temperature distribution of the molten metal in zone 2

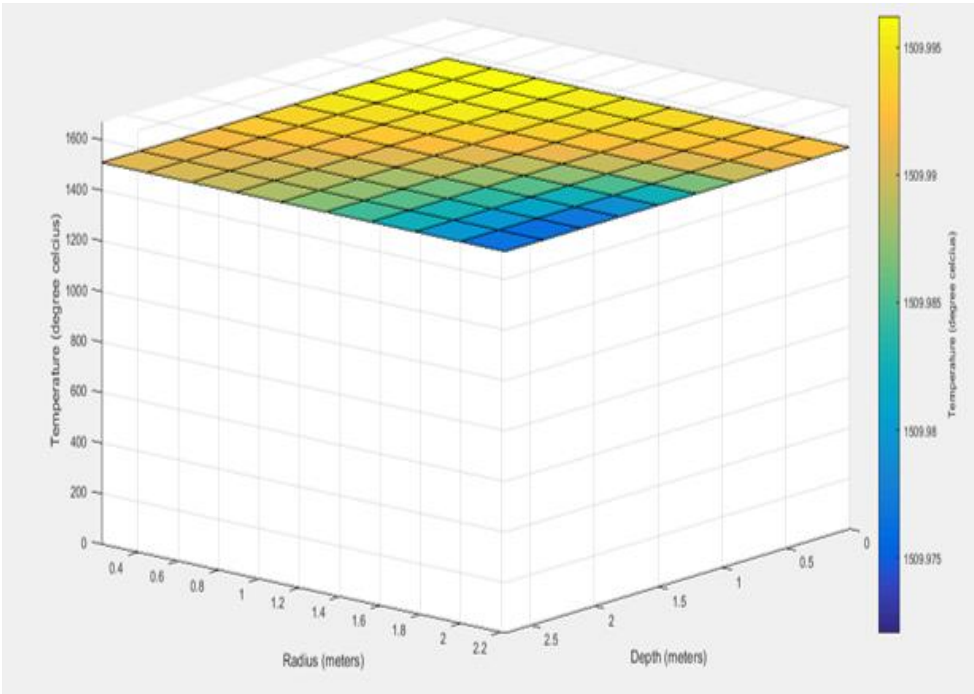

Figure 5: Temperature distribution of the cast metal in zone 2 using surface plot

The initial condition of the zone shows that there is flow of temperature into the shell. Furthermore, Figures 4 and Figure 5 show the contour plot and surface plot respectively. From the Figure 4, the temperature can be predicted as the molten metal flows. It further explains that at a reduced width of 1m to 2.2m there is a steady drop of temperature from 1509.9874^o C to 1509.9764^{o}C and that can be seen clearly from the surface plot, Figure 5.

The yellow patches show the region of high temperature which around the boundary of the shell is 1509.99^{o}C and down to the blue patches of lower temperature. At a depth of about 2.5m the temperature has lost some heat, hence other predictions can be made around the solidifying steel shell.

Figure 6 shows the relationship of temperatures of the respective zones and the zone lengths in meters (26.832m). The graph shows a linear decrease of temperatures of 1546°C to 1488.234°C from the mould down to the solidifying steel shell. There is a sharp change in temperature from 1509.987°C to1499.75°C at a distance of 6.557m due to increase in heat loss. Figure 6 further shows the temperature distribution along the entire set up from the mould to the steel solidifying shell.

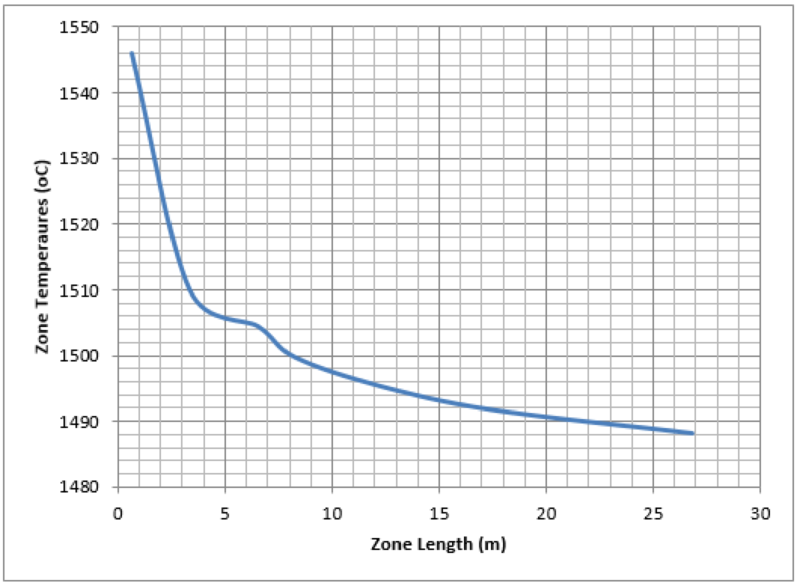

Figure 6: A graph of zone temperatures against zone lengths

To validate the result from this analysis, we compare the results obtained with the results from [4]. To further validate the result obtained from this paper using the Galerkin Finite Element Method, the problem was also solved using the Exact Differential Equation Method. The result obtained is as shown in Figure 7 for the cast region. The figure 7 shows the variation of growth of the solid shell thickness on the ingot for the grade 1 steel of 0.16% C. it is obvious that the results from this work have a very good relationship with that obtained in literature [4]. This comparison was made using the same pouring temperature of 1546^0C and the mould preheat temperature to be 320^0C.

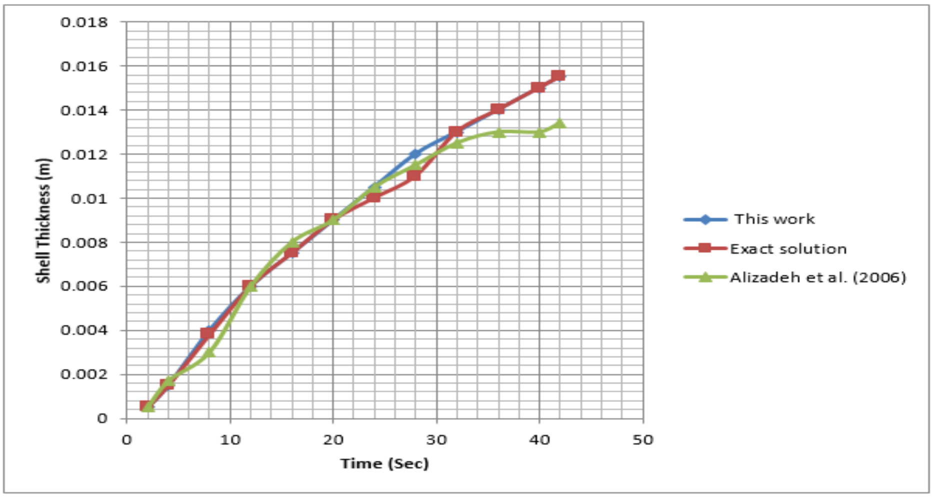

Figure 7: A graph showing result from this work, Exact Differential Equation Method and [4] in the metal cast region

4.0 Conclusion

A finite element model was developed for the 2D conductive heat transfer for continuous casting and the model was used to determine the temperature distribution in the mould and in the solidifying shell region. The solidification time using the conductive heat transfer model was determined and it was observed that solidification started at zone 6 and completely solidified at zone 7 with considerable amount of heat. Using the range of pouring temperatures of 1488^{o}C to 1546^{o}C, the liquid cast completely solidified between 23.6 min and 28 min. The accuracy of the result was validated by comparing the results with existing results in literature. There is a strong agreement between the results from this research with that obtained in literature.

It was observed that the shell thickness linearly increase from 0.0005m to 0.0155m in the solidification of the liquid cast along the shell within a time of 40sec which was due to continuous cooling with water.

The accuracy of the results obtained was admissible which shows that the Garlerkin Finite element method can be used in approximating the temperature distribution, the solidification time and thickness in continuous slab casting using the transient form of the heat conduction equation.

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