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Numerical Investigation of Transient Solidification Behavior of Cast with and without Feeding Aids

Lokesh Baviskar[1] and Dr. R. S. Maurya[2]

[1] *P.G student, Sardar Patel College of Engineering, Mumbai, India.*

[2] *Associate Professor, Sardar Patel College of Engineering, Mumbai, India.*

Abstract

Sand casting is one of the oldest manufacturing process applicable for mass production of varieties of product. Through the pouring cup molten metal is poured into mould cavity which made in same as size of product. The molten metal is then allowed to cool and solidify. There is occurrence of liquid shrinkage and solid shrinkage while solidification of casting take place. The riser which is reservoir of molten metal is placed to compensate this shrinkage of molten metal. To serve this purpose the solidification time of riser should be greater than solidification time of casting. The riser sleeve and hot toping are the most widely used feeding aids which use to elongate solidification time of riser. The objective of the present work is to assess the transient behavior of solidification of cast with and without sleeve (exothermic) and hot-toppings (exothermic). The investigation is executed using commercial software ANSYS Fluent.

Keywords: Sand casting, casting solidification, exothermic sleeve, hottoping, ANSYS Fluent, heat generation rate, hottoping thickness

1. INTRODUCTION

Sand casting is one of the oldest manufacturing process applicable for mass production of varieties of product. Through the pouring cup molten metal is poured into mould cavity which made in same as size of product. The molten metal is then allowed to cool and solidify. There is occurrence of liquid shrinkage and solid shrinkage while solidification of casting take place. To compensate this shrinkage, the reservoir of molten metal is placed above casting which is called as riser. So in simple word the purpose of riser is to supply molten metal to casting when solidification of casting take place. But this purpose can only be serve when casting solidify before riser gets solidify. This means that solidification time of riser should be greater than solidification time of casting. For that casting gating system design is carried out in such manner that will it ensure that riser gets solidify at last. But practically when casting is poured it is just possibility that riser gets solidify at last. So another remedy is to elongate solidification time of riser by used of feeding aids. The riser sleeve and hot toping are the most widely used feeding aids. The purpose of these feeding aids is to improve riser efficiency by controlling heat loss from the riser or by providing an additional heat source to the metal in the riser. The riser sleeve can be either insulating or exothermic or with a combination of both properties. The riser sleeves are made up of thermite materials, initiator and insulating materials. Various suppliers produce these sleeves in different compositions, different size and shapes. As soon as molten metal, contacts with sleeve or hottoping the exothermic reaction take place with the liberation of heat until exothermic material burns. The mushy zone is a transition region between metal which is solidified and which is in liquid state.

Wlodwar et al. [1] conducted various experiment in which involve the surrounding spherical casting with exothermic material lining and corresponding increase in thickness of sleeve lining. He obtain different solidification time for different thickness of lining. In another experimentation Wlodwar et al. found that a sleeve thickness 0.15 times the diameter of the cylinder result in flat shrinkage cavity compare to normally occurring conical shape. All this Wlodwar et al. finding are applicable for particular configuration of geometry and materials, so these finding cannot be generalized. The Foseco [2] recommended sleeve thickness of 0.2 times riser diameter for some categories of sleeve produced by Foseco. Despite the extent of sleeve use, a survey of foundries found that there is lack of consensus on the use of the riser sleeve. Sleeve suppliers use different raw materials of unknown and proprietary compositions and properties in their manufacturing process. As a result application of riser sleeves in foundries is largely based on trusting suppliers, guesswork and trial and error testing [3]. There is no generalized criteria of sleeve thickness for particular casting.

This all leads to use computer casting simulation software for evaluation of effect of riser sleeve and optimization of riser size so that to minimize the defects occurring in the casting. The accurate thermo physical properties of riser sleeve and casting material are required as input data for simulations. These thermophysical properties are either provided by a limited number of suppliers for their products as black box database (hidden from software user) in some commercial casting software like MAGMASOFT or not available. More recently Midea et al. [4] has done investigation on thermophysical data for casting process simulation and have been published temperature dependent curves for density, specific heat and thermal conductivity of several sleeves. But these curves no numerical values are shown on axes so only reader only gets graphical trend of variation of thermal properties with temperature. It was found that thermal conductivity about 4 times more influential than the heat capacity of the sleeve. Iganszak et al. [5] instead of developing temperature dependent data, utilize inverse modelling technique to determined average exothermic sleeve material thermophysical property data. The temperature data in sand mold and steel were obtain by conducting experiments. A computer program was then used to conduct simulations of the castings where all thermophysical properties were iteratively modified until the error between simulation results and measured data is minimized.

R. Hardin et al. [6] studied the effect of sleeve type on casting yield using Magmasoft software. He found that longest solidification time obtain with insulating sleeve while considering 10% safety margin. R. Hardin et al. [7] conducted investigation on determination of thermophysical properties of riser sleeve and casting material using inverse modeling technique of 11 commercial available sleeve. There is no much variation in density and specific heat with respect to temperature. So we can take average and predetermine values of these properties. Iteratively the data for thermal conductivity is developed. MEF is found to be sensitive to superheat and independent of size. Choudari et al. [8] has perform transient thermal analysis using ANSYS software for optimization and analysis of riser in sand casting. Application of sleeve help in reducing riser dimension from 60 mm to 50 mm and thereby increasing the casting yield. Wiwik et al. [9] has done investigation on feeding efficiency between a dome shape and cylinder shape exothermic-insulating sleeve. The casting yield is increased by 90% by dome sleeve greater than cylinder sleeve which have 88% and sand riser which only 19%. A die casting with anti-gravity filling process was numerically investigated using fluent by Yuwen et al. [10] in which Volume of Fluid model used capture filling process. He simulate liquid metal free surface and temperature distribution at various time step. The change in free surface shows that liquid metal is volatile and turbulent at early stage of filling process, when liquid metal contact with mould wall.

Overall sleeve performance depends on the quality and quantity of thermite material present in sleeve. The exothermic heat generation in sleeve and burn time of thermite are the parameter which play important role in determination of riser sleeve effectiveness. Very few literature is observed on the effect of riser sleeve shape on casting performance. There is little work available for investigation of geometrical parameters like thickness of riser sleeve and hottoping on solidification behavior.

2. PROBLEM DEFINITION AND METHODOLOGY

Present problem deals with cast solidification where apart from regular elements of casting system, few other elements are also used to enhance its quality and yield. Use of risers and hot-toppings are very common, which help to increase the casting yield, minimize defects and provides better control on overall casting process. To carry out the investigation a rectangular casting block of dimension 50 mm × 50 mm × 20 mm is considered which is sand casted. An arrangement of mould with feeding element and riser is shown in fig.1. Molten metal (material-ASTM WCB A216) is poured into mould cavity at 1600 °C and solidification takes place. The progress of solidification of molten metal is investigated. The objective of the present work is to assess the transient behavior of solidification of cast with and without sleeve (exothermic) and hot-toppings (exothermic). The investigation is executed using commercial software ANSYS Fluent.

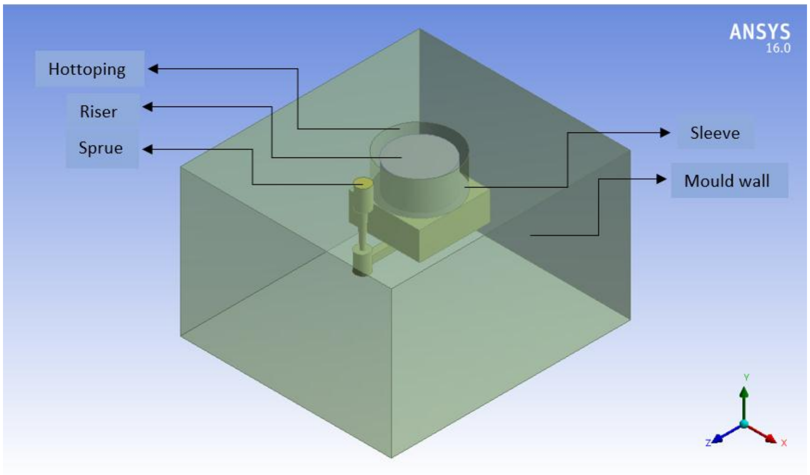


Figure 1: Casting with sand mould

3. THEORETICAL DESIGN OF CASTING SYSTEM

Theoretical design of casting system consist of design of riser, casting gating system and pattern design. The gating system is part of the mould cavity through which the metal is poured to fill the casting impression. Theoretical design of casting is needed to meet following threefold purpose-1) The metal flow rate and direction must be such as to ensure complete filling of the mould before freezing. 2) To avoid entrapment of air, metal oxidation, and mould erosion flow should be smooth and uniform with minimum turbulence. 3) The technique should promote the ideal temperature distribution within the completely filled mould cavity. So that the pattern of subsequent cooling is favorable to feeding. Purpose of riser is to supply molten metal to take care of liquid shrinkage and solid shrinkage. In casting modulus is defined as ratio of volume of casting to surface of casting. Here Riser is design using modulus method. Non-pressurized gating system design is done with gating ratio 1:4:4. Final summary of theoretical design is as shown in table no. 1

Table 1: Casting system dimension

Design parameter	Dimension
Diameter of riser	0.04 m
Height of riser	0.02m
Bottom CS area of sprue	$1.0112 \times 10^{-5} m^2$
Top CS area of Sprue	$2.0224 \times 10^{-5} m^2$
Taper of sprue	0.5
Area of ingate	$4.0448 \times 10^{-5} m^2$
Area of runner	$4.0448 \times 10^{-5} m^2$

4. MATHEMATICAL MODEL

Solidification simulation of casting involves filling of molten metal inside cavity and subsequent solidification of molten metal with respect to time. This process can be described by mass conservation equation, N-S equation, conservation of energy equation, volume of fluid function equation and enthalpy-porosity equation to model solidification process.

- Mass equation : $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} + \frac{\partial p}{\partial t} = 0$ .... (1)

- X-momentum equation

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = \rho g_x - \frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + s_1 \quad \ldots\ldots (2)$$

Y-momentum equation

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = \rho g_y - \frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + s_1 \quad \ldots.. (3)$$

Z-momentum equation

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = \rho g_z - \frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + s_1 \quad \ldots (4)$$

- Energy equation : $\rho c_p\, [\frac{\partial T}{\partial t} + (\vec{V} \cdot \nabla)\, T\,] = k\, \nabla^2 + s_2$ …....(5)

- Volume of fluid : The volume of fluid model can model two or more immiscible fluid phases in terms of volume fraction γ of each of the fluids by solving a single set of mass and momentum equations.

$$\rho = \{\gamma\rho + (1-\gamma)\rho_1\} \quad \ldots\ldots.. (6)$$

$$T = \{\gamma T_1 + (1-\gamma)T_2\} \quad \ldots\ldots.. (7)$$

- Enthalpy-porosity equation : An enthalpy-porosity technique is used for modeling the solidification/melting process. The mushy zone is treated as a "pseudo" porous medium with porosity varying from 0 to 1. In case of fully solidified material in a cell, the porosity becomes zero and thereby the velocity drop to zero. For that purpose additional sink term are added to momentum and energy equation. The momentum sink due to the reduced porosity in the mushy zone takes the following form:

$$s_1 = \frac{(1-\alpha)^2}{(\alpha^3+\epsilon)} A_{mush}\, (\vec{u} - \vec{u}_p) \quad \ldots\ldots. (8)$$

where α is the liquid volume fraction, ϵ is a small number (0.001) to prevent division by zero, Amush is the mushy zone constant, and $\vec{u}_p$ is the solid velocity due to the pulling of solidified material out of the domain.

Sinks are added to all of the energy equations in the mushy and solidified zones to account for the presence of solid matter.

$$s_2 = \frac{(1-\alpha)^2}{(\alpha^3+\epsilon)} A_{mush} \emptyset \qquad \text{...... (9)}$$

Where $\emptyset$ represents the turbulence quantity being solved (k, $\in, \omega$ etc.)

5. NUMERICAL IMPLEMENTATION AND SOLUTION STRATEGY

Numerical implementation involves preprocessing, solver setting and solver execution. Computational domain consists of rectangular casting block, cylindrical riser and gating system surrounded by moulding sand. Over that is domain conformal mesh with 3D tetrahedron elements were generated using ANSYS meshing modeler. The simulation is carried out by employing energy, viscous laminar, multiphase volume of fluid and solidification & melting model. The multiphase volume of fluid model was used to filled casting with material ASTM A216 WCB steel. To capture solidification of molten metal solidification & melting model was used. Thermophysical properties of ASTM A216 WCB carbon steel, moulding sand as shown in the following table no. 2 & 3

Table 2: Properties of ASTM WCB A216

Properties of ASTM WCB A216	
Density	7800 Kg/m^3 (at 273K)
	7400 Kg/m^3 (at 1273K)
	6800 Kg/m^3 (at 1923K)
Specific heat	1025 J/kg K
Thermal conductivity	55 W/m K (at 273K)
	140 W/m K (at 1923K)
Latent heat	192000 J/Kg
Solidus Temperature	1350 °C
Liquidus Temperature	1500 °C

Table 3: Properties of sand and exo sleeve & hottoping

Properties of sand	
Density	1495 Kg/m^3
Specific heat	1172.304 J/kgK
Thermal Conductivity	0.519 W/m K
Exo sleeve & hottoping	
Density	422 kg/m^3
Specific heat	450 J/kg-K
Thermal conductivity	0.35 W/mk
Ignition Temperature	600 ℃
Exothermic Heat Generation	250 KJ/Kg

In simulation process, pouring temperature is 1600℃ ; the sand mold and ambient temperature both set to 27℃ ; pouring rate is 0.4953 m/s using the way of antigravity bottom pouring ; acceleration due gravity is 9.8 m/s^2. Boundary conditions were set as follow:1) Sprue top was set as velocity inlet 2) Riser top was set as pressure outlet3) Sand mould wall was set as wall with convection heat transfer coefficient 20 W/m^2k.

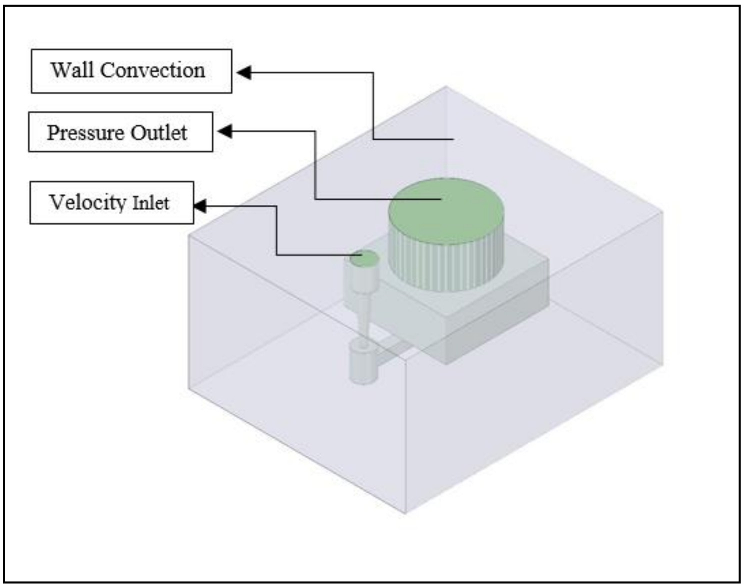


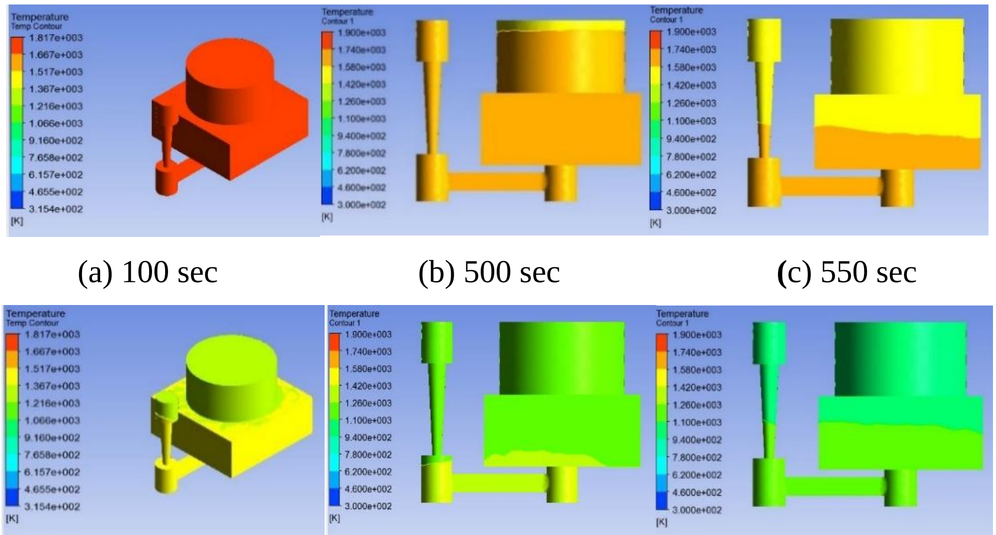
Figure 2 Boundary conditions

For volume of fluid model volume fraction at sprue inlet and riser outlet is set top one and zero respectively. Couple algorithm was used to solve the coupling problem between velocity components and pressure in momentum equations. Momentum, energy were taken as second order upwind scheme while pressure discretization was set to second order. The whole calculation domain state was initialized using standard initialization with phase 2 volume fraction patch to one. Now as casting is filled, multiphase volume of fluid model is turn off. Boundary conditions at sprue inlet and riser outlet are modified to wall condition. Then solver was executed initially with time step 10^{-05} sec once simulation get stable it increases to 1 sec.

6. RESULT AND DISCUSSION

6.1. Transient thermal behavior of cast solidification without sleeve and hot-toppings

Always casting gating system design is carried out in such manner that riser gets solidify at last. But practically when casting is poured it is just possibility that riser gets solidify at last. In casting at different point different cooling rate occurred. Normally highest cooling rate will occurred at near wall and slowest cooling rate is occurred at center or intermediate position. When solidification of casting take place at different point different cooling rate occurred so at different point different temperature exits at that time. The particular region in casting where maximum temperature exist is called as hotspots and this region solidifies at last. To determine solidification time of casting it is necessary to locate hotspot. For that purpose temperature contour at time are plotted as shown in fig. 3



(a) 100 sec (b) 500 sec (c) 550 sec

(d) 1000 sec (e) 1300 sec (f) 1750 sec

Figure 3: Temperature Contour of casting at different instant of time

Time to solidus was found to be 475 sec without exothermic sleeve and hottoping. We can see that directional solidification take place from top of casting to bottom of casting and hotspot occurred at runner. So riser is solidifying before casting and it is not serving it purpose of supplying molten metal. This may be due to heat diffusion through top of mould is more as compare to bottom of mould. To get favorable temperature gradient extra sand is added on the top riser and following cases of simulations are investigated with all simulations setting similar to previous simulation- 1) 70 mm sand above riser 2) 50 mm sand above riser 3) 20mm sand above riser

To determine solidification temperature 5 points are taken along vertical direction in case 1) 70mm sand above riser as shown in fig 4 and graph of Temperature vs Time is plotted as shown in fig.5 Addition of sand above riser top lead to uniform solidification of riser and casting with elongation of solidification time. It is worth to note that in this above case riser and casting solidifying at same rate so solidification curve of all 5 points is overlapping.

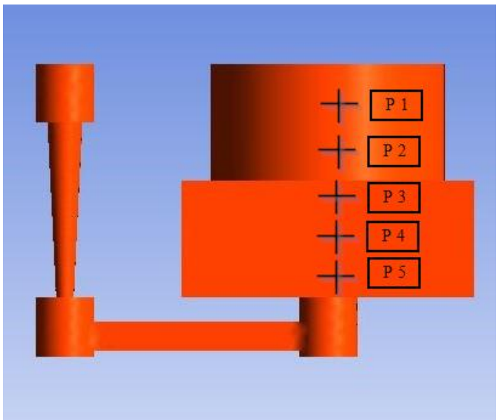


Figure 4. Location of 5 points in casting and riser

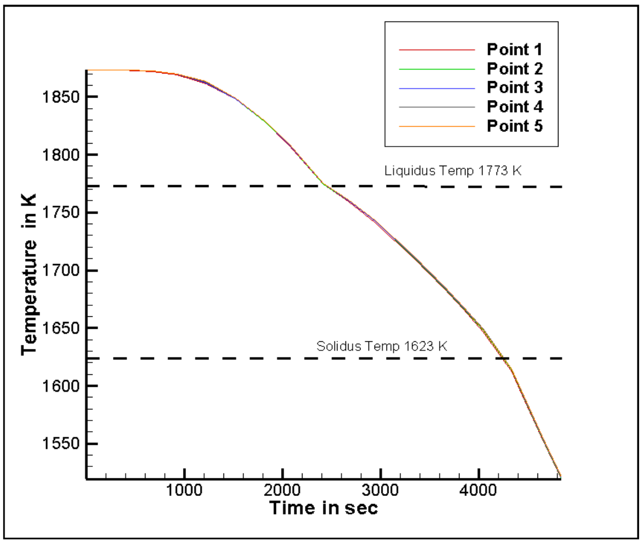


Figure 5. Temp Vs. Time Graph for case 70 mm sand above riser

The direction of solidification is from wall of sand mould to vertical center axis of casting and riser. Similar overlapping solidification curve obtain in other two cases with different solidification time. Result of all three cases is summarize as shown in following table no. 4

Table 4. Result summary of solidification time

Case	Solidification Time
70 mm sand above riser	4800 sec
50 mm sand above riser	4100 sec
20 mm sand above riser	3200 sec

6.2. Transient thermal behavior of cast solidification with sleeve and hot-toppings

The hot toping is another widely used feeding aids. In hot toping thermite material powder is sprayed over riser top surface, similar to exothermic sleeve here also exothermic reaction take place and heat is supplied to riser to elongate its solidification time. Sometimes powder insulating in nature is also mixed with thermite powder to achieve insulation effect at the top riser. In the market the variety of thermal riser sleeve and hottoping are available of unknown material composition in different size and shape. It is heat generation rate of thermite material and burn time on which performance of feeding aids depend instead of geometrical parameter. Here numerical simulation is conducted to investigate the effect of hottoping thickness and heat generation on solidification of riser.

6.2.1. Effect of hottoping thickness

The computational domain involves rectangular casting block with cylindrical riser surrounded by exothermic sleeve of 5mm, at top of riser hot toping of variable thickness is provided and this all domain surrounded by sand mould. In this simulation volumetric heat generation 2637500 w/m^3 was provided inside exothermic sleeve and hottoping for 40 sec. Following cases are simulated – 1) 6 mm hottoping thickness 2) 4 mm hottoping thickness 3) 2 mm hottoping thickness

To determine solidification time of casting it is necessary to locate hotspot. To determine solidification temperature 5 points are taken along vertical direction in case 1) 6mm hottoping thickness as shown in fig 4 and graph of Temperature vs. Time is plotted as shown in fig.6

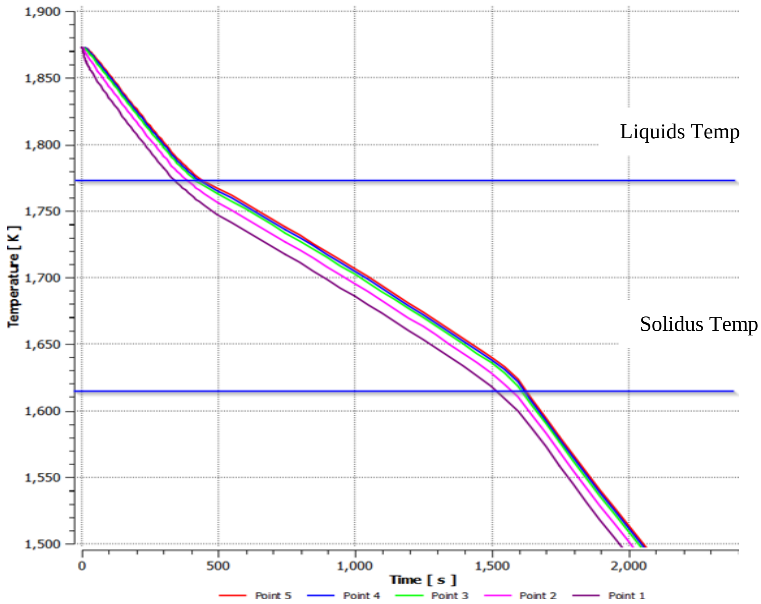


Figure 6. Graph of Temp Vs. Time for Case 1) 6 mm hottoping thickness

Here point P1 and P2 are in riser while P3, P4 and P5 occur in the casting block. From above graph we can see that point P3, P4 and P5 are solidifying before point P1 and P2. So riser is serving it purpose as reservoir. Similar result obtain in other cases. The effect of hottoping thickness on solidification time are summarize as below in table no.5

Table 5: Effect of hottoping thickness on solidification time

Case	Solidification Time
6 mm hot toping thickness	1650 sec
4 mm hot toping thickness	1625 sec
2 mm hot toping thickness	725 sec

Increase in Hottoping thickness lead to elongation in solidification time.

6.2.2. Effect of Variable Heat generation

To evaluate the effect of variable heat generation the computational domain under consideration is rectangular casting block with cylindrical riser surrounded by exothermic sleeve of 5mm, at top of riser 4 mm hot toping is provided and this all domain surrounded by sand mould. Numerical simulation is executed for following cases – 1) Heat Generation rate 1000 KJ/Kg 2) Heat Generation rate 500 KJ/Kg 3) Heat Generation rate 250 KJ/Kg

To determine solidification temperature 5 points are taken along vertical direction in as shown in fig. 4 and graph of Temperature vs. Time is plotted as shown in fig. 7 & 8

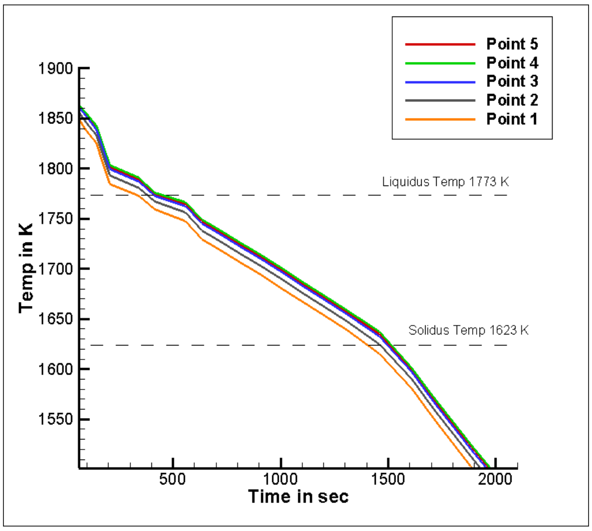


Figure 7. Temp Vs. Time graph case 1) 1000 KJ/Kg

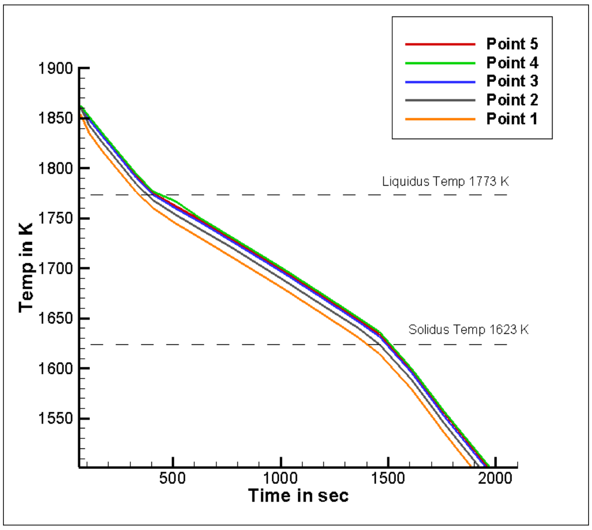


Figure 8. Temp Vs. Time graph case 2) 500 KJ/Kg

Here point P1 and P2 are in riser while P3, P4 and P5 occur in the casting block. From above graph we can see that point P3, P4 and P5 are solidifying before point P1 and P2. So riser is serving it purpose as reservoir. Similar result obtain in other cases. The effect of heat generation on solidification time are summarize as below in table no.6

Table 6 Effect of heat generation on solidification time

Case	Solidification Time
Heat generation rate 1000 KJ/Kg	1525 sec
Heat generation rate 500 KJ/Kg	1550 sec
Heat generation rate 250 KJ/Kg	1650 sec

6. CONCLUSION

- Casting with open riser leads to diffusion of heat from riser at much higher rate comparatively to casting block and results in solidification of riser before solidification of casting block.
- Addition of sand above riser top leads to elongation of solidification time and simultaneous solidification of casting and riser.
- The combination of exothermic sleeve and hottoping leads to formation of favorable temperature gradient. Increase in thickness of hottoping results in elongation of solidification time while increase in heat generation rate leads to decrease in solidification time.

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