**Numerical simulation on heat transfer analysis in zinc solidification process using enthalpy porosity method**

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**Abstract**: The solidificatuion study of metal alloys are very commom than that of pure metal.The research article presented focused on solidification of a pure zinc. The simualations are conducted using Volume of fluid and enthalpy porosity model. This fixed grid method considered is applicable to both pure and metal alloys. The effect of heat transfer analysis during solidification of molten zinc with different thermal boundary conditions are studied. The contours show the location of solid-liquid interface and metal-air interface with time. The transient study of melt fraction and heat flux for different thermal boundary conditions presented to explain the heat transfer analysis with phase change. The simulation also show the shrinkage of solidphase after completion of solidification process.

***Keywords*:** Pure zinc, enthalpy-porosity model, solidification, rectangular cavity.

1. **Introduction**

Zinc is one of the important non-ferrous metals. It is being used in variety of industries and products. Pure zinc is predominantly used as a coating material for corrosion resistance. Zinc is also used for many industrial alloys. Zinc in various forms is used in cosmetics, paints, inks, soaps, pharmaceuticals, plastics, electrical equipment, batteries, and textiles. Zinc is also used as a casting material for various metal products. It is therefore important to understand the melting and solidification process of zinc. The numerical and experimental studies on melting and solidification are available for different phase change materials (PCMs) like: inorganic, organic PCMs, pure and alloys substances. Some of the PCMs having high phase change temperature and some have low melting temperature. The solidification studies are also considered for different casting processes. A large amount of heat is transferred as latent heat in phase change process which affects the macroscopic behaviour of the substance. In this study solidification of zinc is simulated using enthalpy porosity model. Volume of fluid (VOF) is incorporated with enthalpy porosity model to define the PCM and air interface at the open surface.

Bermudez and Otero compared the solidification of aluminium slab using direct chill casting and electromagnetic casting processes. The limitation of the proposed numerical model is fixed grid method[1]. Chakraborty studied the solidification of pure substance water using enthalpy porosity model[2]. The study considered the variation in specific heat in both the phase and showed an well agreement with the prediction made by Kowalewski and Rebow[3]. Bot and Arquis simulated the one dimensional model of deposition and solidification of successive metal layers on a cold surface[4]. The model used for simulation not considered the convective phenomena because of negligible flow time. Tian et. al studied the effect of cooling rate in polymorph selection during solidification of zinc[5]. The study shown the effect of polymorph selection is different at different stage of cooling. Wenyi Hu optimized the casting of AZ31 magnesium slab using direct chill method with different cooling speed[6]. Solidification studies are presented for different metals and alloys like Nickel [7], tin [8] etc. Tomasz and Ewa simulated the solidification of Copper using finite element method. They used front tracking method to locate the solid-liquid interface[9]. Similar numerical studies are also presented by several authors with different boundary conditions [10-13]. Lewis and Ravindran simulated filling and solidification of molten aluminium in spiral and spillage wheel type cavity[14]. They used finite element method with fixed grid for the solidification study. Fixed grid method is advantageous over moving grid. Fixed grid considers the total materials as a single phase and for moving grid the control volume is treated as two phase. In case of alloys more number of materials are present and using moving grid the calculation is complicated. In such situation the fixed grid method is more effective. During casting of metals the impurities are always present in optimum amount and fixed grid method is appropriate in such cases. Literature survey shows that there is very few literature available on solidification of pure metal. The study of phase change for pure metals are important to set a bench mark for alloys. The difference in thermal behaviour of metal and alloys can be studied by performing this type of simulation.

In this paper the authors focused on the fixed grid method for simulation of solidification of pure zinc under different thermal boundary conditions. Volume of fluid (VOF) method is used to describe the interface of air and zinc and enthalpy porosity model is adopted to locate the solid-liquid interface of phase changing material. The proposed model is widely applicable for different thermal boundary conditions as well as different inorganic/organic PCMs, high/low phase change temperature materials. The effect of convection heat transfer coefficient on solidification process and time are compared.The solidification of zinc presented in this research paper studied the effect of convection heat transfer coefficient on solidification time.

1. **Mathematical model and computational model**

Phase-change processes come under moving boundary problem. The change in density due to cooling and phase change, the velocity suppression occurs which results in a non-linear interface. A axisymmetric rectangular cavity has been chosen to the study of solidification process of molten zinc. The size of the cavity is 28mm×78mm. The size of cavity is very small in order to minimize the computation time. The cavity is filled with molten zinc. The molten zinc is initially at a temperature which is 4.5 degree higher than that of mean solidification temperature. The study has been performed for different convection heat transfer coefficient. The cavity is exposed to air during the solidification process. Properties of molten zinc are chosen as commercially available zinc. The density of solid zinc is 713.4 kg/m3 and 692.7 kg/m3 for liquid zinc, specific heat 900.1 J/kg.K, thermal conductivity 164W/m.K, viscosity is 0.00358 kg.m/s, latent heat 109kJ/kg, solidus temperature is 693K and liquidus temperature is 698K. Commercial software Ansys-fluent16.2 is considered for numerical simulation of the casting process. VOF model has been used to describe the zinc-air system with a moving internal surface and no inter penetration of two media (air and zinc). Enthalpy-porosity model is used to locate solid-liquid interface in the phase change region. The fixed-grid enthalpy-porosity method describes velocity suppression because at solid phase velocity is zero[15]. The no-slip boundary condition is maintained at the walls. Axisymetric, laminar, and incompressible flow within the cavity is assumed during the simulation proces. The thermo-physical properties of the materials are constant at solid and liquid phases except density of the zinc. The source terms of the momentum equations are used to model the flow through the porous medium, near the solid-liquid interface. The value of mushy zone constant is taken as 105 [16].

The governing equations used to explain the solidification phenomena are

**Continuity equation:**

(1)

In the above eqn. 1 the volume fraction of secondary material PCM molten zinc is denoted by α. The value of αis one at solid/liquid zinc interface and at zinc-air interface the value of α lies between zero and one. The volume fraction eqn. 1 will not be solved for the primary phase (air); the primary-phase volume fraction will be computed based on the following constraint

(2)

**Momentum balance equation:**

(3)

is the density of cell calculated at reference temperature .

Energy balance equation:

(4)

ρ, k and μ denote the density, thermal conductivity and dynamic viscosity of molten zinc and air mixture respectively[17]. The momentum source term is *Si*, ui is the velocity component, xi is a Cartesian coordinate, and h is the specific enthalpy of both the air and zinc respectively in specified region. The Eq. 3 and Eq. 4 are applicable for air, zinc and their interface.

The change in enthalpy is defined as: . is enthalpy at reference temperature . L is the latent-heat for solid-liquid phase change of zinc, and γ is the liquid fraction in computational cell during the phase-change over a range of temperatures and defined by the following relations:

(5)

The source term in momentum is porosity function and defined using Carman-Kozeny equation for flow through porous media and the source is[18]:

(6)

C in Eq. 6 is called mushy zone constant.

SIMPLE pressure-velocity coupling scheme is used to solved the momentum, continuity and energy equations. Discretization Scheme used are second order upwind for momentum, PRESTO for pressure, Geo-reconstruct for volume Fraction and second order upwind energy. The boundary conditions are : convection heat loss at surrounding temperature 300K and the top of the cavity is open and assumed to be at atmospheric pressure condition. The initial temperature of the phase change material on kept 427οC which around is 4.5οC higher than the mean solidus temperature of pure zinc.

The simulation is repeated with difference time step and gridinpendency is also checked to establish the model. The results are shown for maximum time step 0.001sec and with minimum cells 25056. The convergence in each time step has been checked with the convergence criterion of 10-3for velocity, continuity and 10-6 for energy. The mathematical model is solved for different convection heat transfer coefficient at wall boundary.

1. **Results and discussion**

The casting or solidification of pure zinc is studied for different boundary conditions. In this research article solidification of superheated zinc in a rectangular cavity are simulated. The solidus and liquidus temperature of zinc is taken as 420°C and 425°C respectively. The solidification of zinc is a very fast process. The solidification of zinc is studied experimentally and the process is very fast except solidification time no other experimental data are recorded. Therefore, the simulation of solidification process is required for investigation of complete casting process.

For numerical simulation of solidification process the initial temperature of molten zinc is taken as 427°C (700K). Fig 1 shows the solidification time required for zinc under different thermal boundary conditions. These boundary conditions are: solidification with convection heat transfer coefficient (htc) 600 W/m2.K at side and bottom walls, htc of 300 W/m2.K at side and bottom walls, htc of 600 W/m2.K at side and insulated bottom walls, htc of 300 W/m2.K at side and insulated bottom walls, insulated bottom and constant side wall temperature (300K) and htc of 200 W/m2.K at side and insulated bottom walls. The solidification time required is minimum for constant side and insulated bottom wall temperature (300K) and it is around 3.5 sec. The solidification time is around 36 sec (maximum) for wall convection heat transfer coefficient 200 W/m2.K with and without bottom insulation. It is observed from the Fig 1 that the solidification time is not affected by the bottom insulation. The time required for solidification is same for same side wall convection heat transfer coefficient. The reason behind it is the solidification starts from the both the vertical wall and the width of the cavity is less than the height or vertical wall, therefore insulated bottom wall is able to minimize the effect of cold vertical wall.

**E:\simulation files\zinc casting\mf of zinc.tif**

**Fig 1: Melt fraction of zinc under different boundary conditions**

The variations of heat flux with time are not similar for all convection boundary condition. Fig 2 shows the variation of heat flux. The negative sign of heat flux represents the heat loss from the control volume or cavity. The figure concludes that the heat flux from the cavity decreases as solidification proceeds. The trend of heat flux change is almost linear for convection heat transfer coefficient 200 and 300 W/m2.K (with and without bottom insulation) and the trend of heat flux is nonlinear for high heat transfer coefficient 600 W/m2.K (with and without bottom insulation). The slope of heat flux curve is increasing with increase in heat transfer coefficient and slope becomes variable for higher convection heat transfer coefficient.

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**Fig 2: Heat flux variation with time for different wall convection thermal boundary condition**

The contours of melt fraction with time is shown in Fig 3. The red colour represents complete liquid phase and blue colour represents complete solid phase. The half cavity is presented in figure. The contours are shown for solidification with convection heat transfer coefficient (htc) 200 W/m2.K at side and insulated bottom walls. It is observed that solidification starts at top of side wall due the effect of cold vertical temperature and atmospheric air present at the open top of the cavity. With time the thickness of solid phase starts increasing from vertical wall. The thickness of solid phase is not uniform over the vertical wall, due to increase in density of cold metal the thickness of solid zinc is higher in bottom than that of top. Towards the end of solidification the thickness of solid phase is minimum at the middle of the cavity and highest the bottom.

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**Fig 3: Contour of melt fraction of zinc in half cavity**

1. **Conclusion:**

Numerical study helps to identify and analyse each step of a process. Specially for very fast processes numerical simulations are advangeous. It is the safe and economical way of process investigation. In this article the solidification of pure zinc is studied for different convection boundary condition. The results shows the solidification process is vary. The solidification of any high temperature PCM is always very fast. The results also show that bottom insulation is not affecting the time of solidification for same convection heat transfer coefficient. The melting time is maximum for lowest htc (200W/m2.K) and minimum for constant cavity wall temperature, 300K. Such studies can be extended to determine molecular behaviour of metal. The solidification of zinc alloys can also be investigated and compared with pure zinc using this fixed grid enthalpy porosity model.

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