Mould Cavity Layout Optimization in Sand Casting

M.Tech Dissertation

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Abstract

The productivity and yield of sand casting process can be improved by increasing the number of cavities in a given size of mould box. The main challenge lies in finding the optimum number of cavities for a multi cavity mould such that quality is not compromised.

Number of cavities and their layout in a given mould depends on two main parameters, that is, cavity-cavity gap and cavity-wall gap. Solidification time of a casting is affected by the change in cavity-cavity and cavity-wall gap in the case of multi cavity mould. This means that these gaps affect the solidification rate of a casting. Productivity and mechanical properties of a casting are the functions of its solidification rate. To get better mechanical properties and productivity, the solidification rate of the casting should be optimum. The values of the gaps corresponding to optimum value of solidification time are optimum. Heat transfer through the casting and mould during solidification decides the solidification time of casting. The variation of solidification time with these gaps has been calculated and studied in this research work. Transient thermal analysis of casting solidification is done using Finite element method tools like ANSYS and ABAQUS, to calculate the optimum value of the above gaps in sand mould.

Experimental validation is carried out to validate the simulated results. Thermocouples are used to measure temperatures at some particular points inside the mould, during the solidification of casting. These temperature profiles are then compared with the profiles obtained from simulation. The numerical results are found to be in good agreement with the experimental ones. A methodology is developed for optimizing mould cavity layout for sand mould. A case study is solved using the methodology and optimum cavity-cavity gap is calculated for it.

Keywords: transient thermal analysis; FEM; sand casting; cavity-cavity gap; cavity-wall gap; simulation; solidification

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Chapter 1
Introduction

This chapter contains the basic introduction of metal casting, mould construction, mould design and casting solidification.

1.1 Metal Casting

Metal casting is a versatile manufacturing process in which liquefied metal is poured into previously prepared mould cavity and allowed to solidify. Subsequently the product is taken out of mould cavity, trimmed and cleaned to shape. Casting can produce products from few grams to several hundred tons and from simple shapes like watch cases to most complex parts like engine blocks. It is a near net shape manufacturing process involving less or no further operations. Almost any metal or alloy which can be easily melted is castable.

Casting has many process variations depending upon the material, the type of pattern, mould and the pouring technique like sand casting, investment casting, die casting, squeeze casting and lost foam casting. Sand casting is the most widely used process which can be used to produce intricate parts in almost every metal that can be melted. According to worldwide census of casting production over 75 million metric tons of castings are produced annually. India is the fourth largest producer of castings.

For successful production of castings one needs knowledge in the following operations:

- Preparation of moulds and patterns
- Melting and pouring of liquefied metal
- Solidification and further cooling to room temperature
- Inspection and quality control

One of the major concerns of the foundries worldwide today is to produce castings of superior quality with minimum rejections (Ravi, 1996). Because of the complex physics involved and the number of steps needed to produce a casting, the parameters which govern

the quality of a casting are huge in number. The major sources of defects arise from inappropriate design of the part, feeding and gating system. The defects arising due to bad design are mainly because of isolated thick and thin sections or sudden increase in the section thickness. Solidification related defects arise mainly because of improper part design or improper method design (feeding and gating systems).

1.2 Mould Construction

Casting can be produced in either permanent metal mould or expandable refractory mould. The use of metal moulds or dies for making parts in die casting has certain major limitations. The continual contact of die with molten metal reduces the die life, as it is subjected to very high temperature. Therefore die casting is generally preferred for low melting point metals. In addition, the cost of die manufacture can only be sustained by large production. Thus greater part of the output of the foundry industry consists of sand castings.

The manufacture of sand castings mainly consists of three stages: production of mould, melting, casting and finishing operations. The first major stage in founding is the production of mould. It contains a cavity, which is similar to the shape of the required part and has a planned provision for metal flow and feeding. For this purpose a pattern is required, along with other foundry equipments ranging from moulding and core making machines to moulding boxes and hand tools. The moulding procedure for a particular casting is largely determined by the means chosen at the outset of pattern removal and embodied in the construction of pattern. For this reason, decisions as to the entire manufacturing technique should be taken at the earliest stage, including consideration of the orientation of the casting for gating and feeding as well as pattern withdrawal. A rational choice can be made of the system of parting lines, cores and other feature to achieve overall economy in manufacture (Beeley, 2001).

A multi-part moulding box (known as a casting flask, the top and bottom halves of which are known respectively as the cope and drag) is prepared to receive the pattern. Moulding boxes are made in segments that may be latched to each other. For a simple object - flat on one side – the lower portion of the box, closed at the bottom, will be filled with prepared casting sand or green sand - a slightly moist mixture of sand and clay. The sand is packed in through a vibratory process called ramming. The surface of the sand may then be stabilized with a sizing compound. The pattern is placed on the sand and another moulding box segment is

added. Additional sand is rammed over and around the pattern. Finally a cover is placed on the box and it is turned and unlatched, so that the halves of the mould may be parted and the
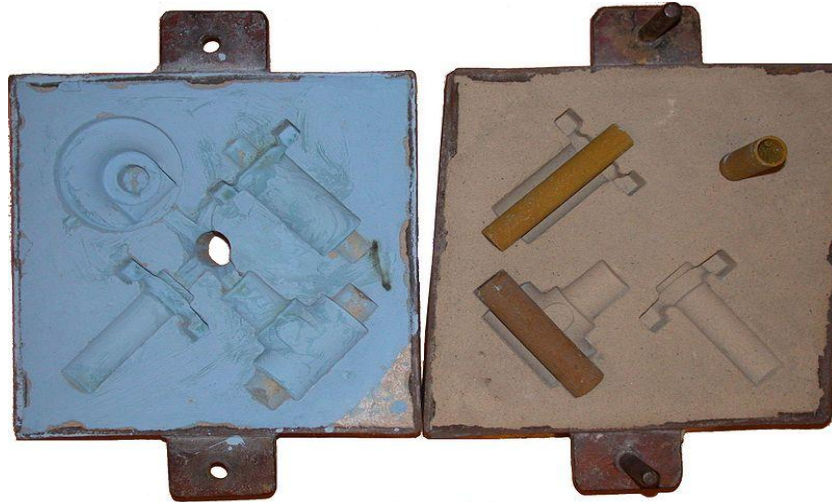
Fig. 1.1 Casting layout in multi cavity sand mould (Courtesy Jintan Inc, 2009)

pattern with its sprue and vent patterns removed. The box is closed again. This forms a "green" mould which must be dried to receive the hot metal. In some cases, the sand may be oiled instead of moistened, which makes possible casting without waiting for the sand to dry. Sand may also be bonded by chemical binders, such as furnace resins or amine-hardened resins.

1.3 Mould Design

A decision which greatly influences production costs concerns the size of mould unit to be adopted and the arrangement of patterns in relation to mould dimension. The objective should be to employ the largest size of mould that can be conveniently handled by the plant, and to achieve intensive use of mould space through a high packing density of castings (Beeley, 2001). This reduces the number of moulding operations and minimizes sand consumption. These objectives are achieved by the use, whenever possible, of multiple casting moulds in which two or more patterns are grouped round a common sprue or feeding system (*Fig. 1.1*).

Advantages of multi cavity mould are as follows:

Better Utilization of mould material: The utilization of mould material is measured in terms of metal to sand ratio. More the metal to sand ratio, more is the mould material

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utilization and more is the packing density. Therefore more castings can be made from a fixed amount of sand volume which leads to cost reduction.

Metal to sand ratio: It is the ratio of the sum of weight of casting(s), weight of gating system and weight of feeder(s) to the weight of sand used in a mould.

$$\text{M/S Ratio} = \frac{\rho_{metal}(N_c V_c + V_f + V_g)}{\rho_{sand}[V_{mould} - (N_c V_c + V_f + V_g)]} \tag{1.1}$$

ρ_{metal} = Density of metal

ρ_{mould} = Density of mould

V_c = Volume of casting

V_f = Volume of feeder

V_g = Volume of gating system

V_{mould} = Volume of mould

N_c = Number of castings in mould

Higher Yield: Yield is the ratio of the casting volume to the sum of casting volume and gating volume. Better the yield, better is the productivity. Multi cavity mould has higher yield than single cavity mould because common feeders and gating system can be used.

$$Yield = \frac{N_c v_c}{(N_c v_c + \sum_i v_{fg})} \tag{1.2}$$

Reduce production time per casting: Since more castings are formed in a single cycle of operation, production time per casting is reduced.

Multi cavity moulds are preferred when the castings are small compared to the smallest size of production moulds and the production quantities are large. The mould cavity layout is usually taken up after deciding the casting orientation and parting.

The number of cavities and the orientation depends on two main parameters of a mould, which are as follows:

- Cavity-Cavity Gap
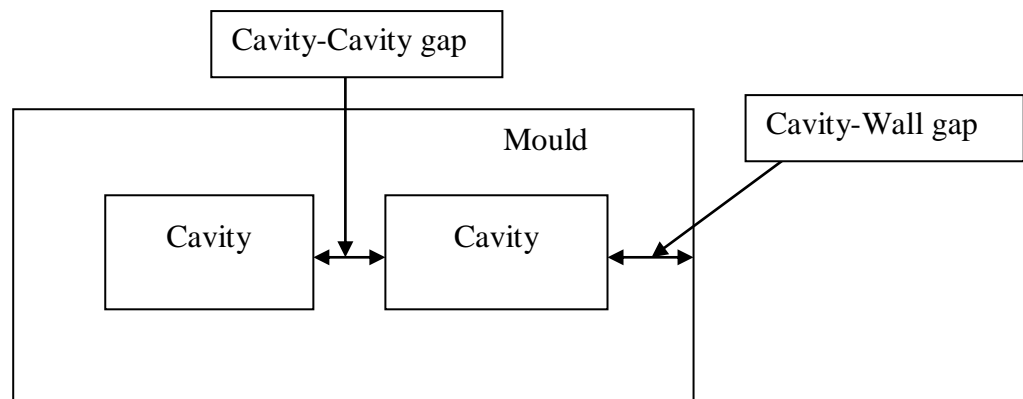
- Cavity-Wall Gap

Fig. 1.2 Cavity-cavity and cavity-wall gap in mould

The cavity-cavity gap is the minimum distance between two adjacent cavities and cavity-wall gap is distance from any cavity to the nearest wall edge (*Fig. 1.2*). The minimum gaps must be sufficient to

1. Prevent damage to the mould during handling and casting.
2. Allow adequate heat transfer so that local hot spots are not formed in the portion of casting close to another cavity.
3. Enable rapid freezing of castings to maximise mechanical properties. If the castings are too close they might suffer delayed cooling that would impair mechanical properties.

The heat flow rate during casting solidification is affected by cavity - cavity gap and cavity - wall gap. So there is a need to study solidification of casting and its behaviour. Next section discusses the same.

1.4 Casting Solidification

Solidification in all castings begins with the initiation of crystallization at the mould walls shortly after casting is poured, thus forming a thin layer of solid metal there, solidification proceeds by gradual thickening of this layer of solid metal. During the freezing period, the

solid and liquid portions of the casting are separated by a sharp line of demarcation-the solidification front-which advances steadily from the surfaces to the centre of the castings.

As the molten metal is poured in the sand mould it starts losing heat to the mould material. Heat lost during solidification can be divided into three distinct phases

1. From pouring temperature to liquidus temperature
2. Latent heat release
3. From solidus to ambient temperature

The heat rejected by the liquid metal is dissipated through the mould wall.
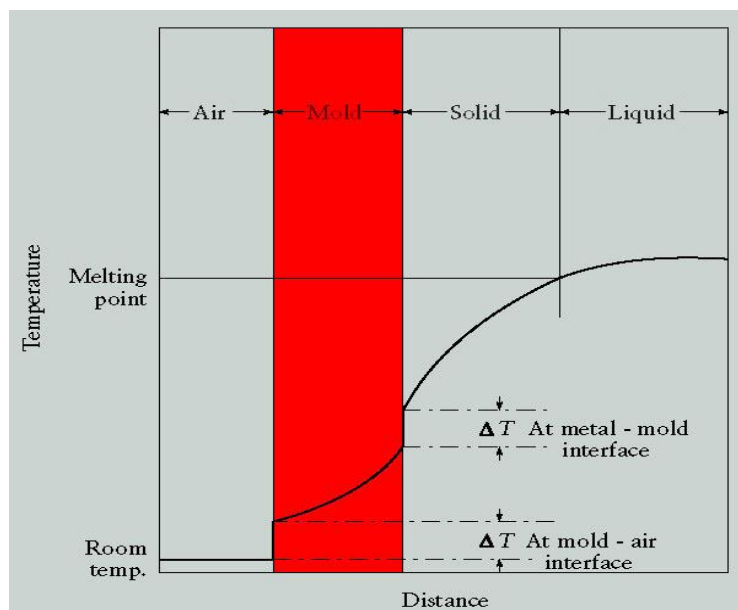
Fig.1.3. Temperature distribution in a mould

The solidification process is quite complicated, especially when complex geometry, freezing of alloys and temperature dependent thermal properties are considered. As an approximation the temperature at the surface of an insulating mould adjacent to solidifying metal is assumed equal to the freezing point of that metal. Because the thermal conductivity of the sand mould is only 1-2% that of the metal, practically all of the thermal resistance to the heat transfer is within the mould.

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From the above discussion it is clear that mould design is very significant in improving the yield and in reducing the defects in casting. Therefore there is a need of optimizing the design of mould to improve the productivity of a foundry. Deciding the optimum number of cavities in a mould is very important in mould designing for a multi cavity mould. In this work, we have developed a methodology for optimizing the cavity-wall and cavity-cavity gap for simple castings, which helps in deciding the mould cavity layout and the number of cavities in a mould.

1.5 Organization of Report

The report is organised in six chapters. The first chapter contains the introduction about metal casting, mould design, mould construction and casting solidification. The second chapter covers the literature reviewed in the area of casting solidification and its numerical modelling. In the third chapter problem and the research approach are defined. The fourth chapter discusses the solidification simulation of simple castings using FEM and their validation with experiments. The fifth chapter presents criteria and a methodology to optimize the cavity-cavity layout of a mould. The last chapter contains the summary of the report and future scope of the work.

Chapter 2
Literature Review

In this chapter basic mechanisms of heat transfer in casting are discussed. This includes heat flow in metal casting process and the types of resistances offered to the flow of heat are studied. Theoretical equation for calculation of solidification time of casting is discussed. Work performed on numerical modelling of casting solidification is also discussed in this chapter.

2.1 Basic mechanisms of heat transfer

They include the following three modes:

2.1.1 Conduction: In the context of metal casting, conduction is the mechanism by which heat is transferred within the solidifying metal and the mould. Conduction can be steady state or transient state. In casting application, transient conduction is more prevalent.

Heat conducted through a medium is given by

$$Q = \frac{kA}{t}(\Delta T) \tag{2.1}$$

Where

Q = Heat flow

k = Thermal conductivity of the medium

A = Area through which heat is flowing

t = Thickness of the medium through which heat is flowing

ΔT = Temperature difference between two surfaces.

2.1.2 Convection: Convection mode of heat transfer is considered in many contexts like

- Heat transferred within liquid metal
- Heat lost from outer surface of the mould
- Heat transferred at metal-mould interface

Heat transfer at the outer surface of the mould is assumed to take place by natural convection and radiation. The heat transfer value is given by:

$$q = h(T - T_\infty) \qquad (2.2)$$

Where

q = Heat flux

h = Heat transfer coefficient

T = The mould surface temperature

T_∞ = Ambient temperature

2.1.3 Radiation: In contrast to conduction and convection, which involve transport of energy through a material, energy may also be transferred through a vacuum. The mechanism is by electromagnetic radiation, and is specifically called thermal radiation. Radiation occurs on the outer surfaces of the mould and at casting-mould interface.

The net radiant exchange between two surfaces is given by:

$$Q = \varepsilon_1 \sigma A_1 (T_1^4 - T_2^4) \qquad (2.3)$$

Where

ε_1 is the emmisivity of the surface

σ is the Stefan-Boltzmann constant = 5.67×10^{-8} Wm^{-2}K^{-4}

T_1 and T_2 are the temperatures of the two bodies, which are mould and air.

2.2 Heat Transfer in Metal Casting

The hot liquid metal takes time to lose its heat and solidify. The rate at which it loses heat is controlled by the number of resistances to heat flow (*Fig. 2.1*)
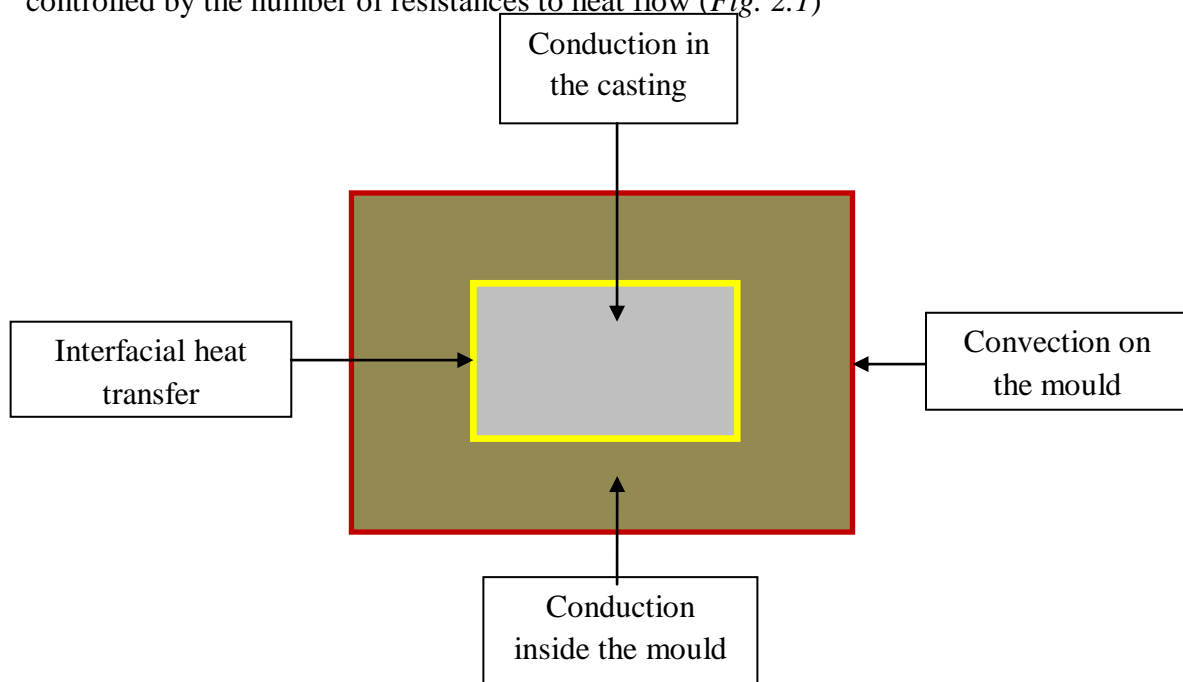
Fig. 2.1 Schematic diagram of heat transfer in a sand mould

The resistances to heat flow from the interior of the casting are

1. The liquid
2. The solidified metal
3. The metal-mould interface
4. The mould
5. The surroundings of the mould

As it happens, in nearly all cases of interest, resistance 1 is negligible, as a result of bulk flow by forced convection during filling and thermal convection during cooling. The turbulent flow and mixing quickly transport heat and so smooth out temperature gradients.

In many instances, resistance 5 is also negligible in practice. For instance, for normal sand moulds the environment of the mould does not affect solidification, since the mould becomes hardly warm on its outer surface by the time that a steel casting has solidified inside. However there are of course a number of exceptions to this general rule all of which related to various kinds of thin-walled moulds, which, because of thinness of mould shell, are somewhat sensitive to their environment (Campbell, 1991).

Therefore the fundamental resistances to heat flow from castings are resistance 2, 3 and 4. The effects of all three simultaneously can be simulated with varying degree of success by computers. However, the problem is both physically and mathematically complex, especially for casting of complex geometry.

Resistance in Casting

For the unidirectional flow of heat from a metal poured exactly at its melting point T_m against a mould wall initially at temperature T_o, the transient heat flow problem is described by the partial differential equation, where α_s is the thermal diffusivity of the solid

$$\frac{\partial T}{\partial t} = \alpha_s \frac{\partial^2 T}{\partial x^2} \tag{2.4}$$

The boundary conditions are x=0, T=T_o; at x=S, T=T_m; and at the solidification front, the rate of heat evolution must balance the rate of conduction down the temperature gradient as follows

$$H\rho_s \left(\frac{\partial S}{\partial T} \right) = K_s \left(\frac{\partial T}{\partial x} \right)_{x=s} \tag{2.5}$$

Where K_s is the thermal conductivity of the solid, S is the thickness of the metal solidified.

Resistance at Metal-Mould Interface

A perfect contact between the metal and the mould surfaces may not be realized in actual practice as the surface irregularities of the solidifying skin result in irregular contacts to be established between the die-wall and the skin. The degree of thermal resistance at the interface is a function of actual contact area, thermal and physical properties of the materials in contact and interstitial fluid present in the voids formed by the two contacting surfaces. The thermal resistance to heat transfer results in a temperature drop at the interface (Prabhu, 2005). The heat transfer at the interface can be characterized either by interfacial heat flux q or by an interfacial heat transfer coefficient h, defined as the ratio of the interfacial heat flux to the temperature drop at the interface:

$$h = q/\Delta T \tag{2.6}$$

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When conditions are favourable, a skin of solidifying casting may physically separate from the mould wall resulting in a gap of finite thickness. The mould configuration and Biot number have been shown to be important parameters affecting the formation of the gap. Once the air gap forms, the heat transfer across the interface drops rapidly. Conduction is the predominant mode of heat transfer through the gap at lower temperatures. While the radiation heat transfer depends on the surface temperatures and emissivities, conduction heat transfer depends on the thermal conductivity of the gas in the gap and the air gap size as well.

The heat transfer coefficients due to radiation (h_r) and conduction (h_c) are expressed as

$$h_r = \frac{(T_c^2 + T_m^2)(T_c + T_m)}{\dfrac{1}{\varepsilon_c} + \dfrac{1}{\varepsilon_m} - 1} \tag{2.7}$$

$$h_c = \frac{k_g}{\delta} \tag{2.8}$$

T_c and T_m are the casting surface and mould surface temperatures, respectively; ε_c and ε_r are the emissivities of the casting and mould surfaces; and k_g and δ are the thermal conductivity of the gas in the gap and the width of the air gap, respectively (Prabhu, 2005).

Since molten casting metal is poured into the mould cavity, it is initially in the liquid state. Metal with high fluidity quickly becomes very viscous in the early stage of solidification, and later completely solidifies. During this process, a gap is formed between the casting metal and mould.

The gap is formed due to the following reasons

- The thermal expansion of a casting metal and mould are different
- Some of the air initially in the mould cavity cannot escape through the mould and is trapped between the mould and casting
- The binder in the mould materials and coatings on the inner surface of the mould may evaporate or burn due to high temperature which contributes as an additional source of gases between the metal and mould

Pouring the liquid metal in sand mould cavity, the dilation due to heating and drying of the mould causes the inner surface of the mould cavity to move outward. The initial cooling rate of metal in sand mould is quite low compared to that in the metallic mould due to which the metal remains in liquid state for longer time. The liquid metal tries to follow the outward movement of the mould wall, till sufficiently thick solid skin is formed. After this the liquid metal will no longer follow the mould wall movement but it will move inward due to contraction, giving rise to the air gap at the mould metal interface.

The air gap formed at the metal-mould interface offers considerable resistance to the cooling process. It controls the total solidification pattern of castings and thereby affects the microstructure and quality of castings. Due to this, it has drawn considerable amount of interest among the researchers in this field.

<u>Resistance in Mould</u>

Castings made in silica sand mould are generally controlled during freezing by the rate at which heat can be absorbed by the mould. The sand mould acts like an insulator, keeping the casting warm. Investment and plaster mould are even more insulating, avoiding premature cooling of metal and aiding fluidity, giving excellent ability to fill thin sections for which these casting process are renowned.

The conduction heat flux in a mould is expressed with the usual rate equation:

$$q = -k \frac{\partial T}{\partial x} \tag{2.9}$$

Since the situation is transient, the temperature distribution is non-linear, and the temperature should satisfy the following equation. Assuming one dimensional conduction in x direction

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{2.10}$$

2.3 Heat Flow and Solidification of Casting

The heat rejected by liquid metal is dissipated through the mould wall. The heat released as a result of cooling and solidification of the liquid metal passes through different layers. The thermal resistance which govern the entire solidification process are those of the liquid, the solidified metal, the mould metal interface, the mould, the ambient air.

Assumptions

- The flow of heat is unidirectional, and the mould is semi-infinite.
- Properties are not temperature dependent and remain uniform throughout the solidification process.
- The metal is in complete contact with the mould surface.
- The metal mould interface temperature remains constant (Solidus temperature) throughout the solidification process.

At time t=0 the liquid metal is poured at temperature T_p into the mould. Since the metal which comes in the contact with the mould wall and solidifies instantly therefore temperature of the interface reaches the solidus temperature, that is, T_s. T_o is the room temperature. Due to this immediately very steep thermal gradient heat conduction starts (Porier et al., 1994).

Now according to the equation discussed in the resistance offered by the mould

$$\partial T / \partial t = \alpha \, \partial^2 T / \partial x^2 \tag{2.11}$$

To get a particular solution for T(x,t) without any integration constants, we specify an initial condition and two boundary conditions as follows

Initial Condition

$$T(x, 0) = T_p \quad \text{at} \quad x \geq 0 \tag{2.12}$$

$T_x(t)$ is the temperature at a distance x from the mould face at an instant t

Boundary Conditions

$$T(o, t) = T_o \tag{2.13}$$

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$$T(\infty, t) = T_0 \qquad (2.14)$$

The solution that satisfies equation (2.11) - (2.14) is

$$T_x(t) = T_0 + (T_s - T_0)[1 - erf \frac{x}{2\sqrt{\alpha t}}] \qquad (2.15)$$

erf (z) is called the error function. The function is very useful for heat conduction problems in semi-infinite mediums

$$erf(z) = \frac{2}{\sqrt{\pi}}(z - z^3/3.1! + z^5/5.2! - z^7/7.3! + \ldots) \qquad (2.16)$$

α is thermal diffusivity of the mould material and is equal to $k/\rho c$.

k = Thermal conductivity of the mould material

ρ = Density of the mould material

c_m = Specific heat of the mould material

Rate of heat flow through any face of any instant t is given by

$$Q = -kA \frac{\partial T_x}{\partial x} (x=0) \qquad (2.17)$$

A is the cross section area of the mould–metal interface (approximately the surface area of casting). Using equations 2.15 and 2.17 we get

$$Q = \frac{kA(T_s - T_o)}{\sqrt{\pi \alpha t}} \qquad (2.18)$$

Thus the total heat flow across the mould face up to a certain time t_o is

$$Q_{t_o} = \int_0^{t_o} Q dt = \frac{2Ak(T_s - T_o)\sqrt{t_0}}{\sqrt{\pi \alpha t}} \qquad (2.19)$$

Heat rejected by the liquid metal until solidification is given by

$$Q_R = \rho_m V[L + c_m(T_p - T_s)] \qquad (2.20)$$

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Solidification time t_s is obtained by equating (2.19) and (2.20)

$$\frac{2Ak(T_s - T_o)}{\sqrt{\pi\alpha}}\sqrt{t_s} = \rho_m V[L + c_m(T_p - T_s)] \tag{2.21}$$

or

$$t_s = \gamma(\frac{V}{A})^2 \tag{2.22}$$

Where constant γ is given by

$$\gamma = \{\rho_m\sqrt{\pi\alpha}[L + c_m(T_p - T_s)]/2k(T_s - T_o)\}^2 \tag{2.23}$$

2.4 Mould Temperature Analysis

Mould Temperature analysis is done using the above equations for a single case. As an example, consider a steel cube of side 100 mm cast in a sand mould of thickness 50 mm .Temperature is to be calculated at different points from the interface in the sand mold after solidification. Temperature at the interface is assumed to be solidus temperature.

Layers of 10 mm are taken and temperature and heat released is found after each layer. Initial temperature of the mould is room temperature, that is, 300 K. T_s, the solidus temperature of steel = 1767 K. α is thermal diffusivity of mould which is $k/\rho c$. k is thermal conductivity of sand = 0.61 J/mKs, ρ is the density of sand = 1600 kg/m^3 and c is the specific heat = 1130 J/KgK . Since the situation is transient, the temperature distribution is nonlinear.
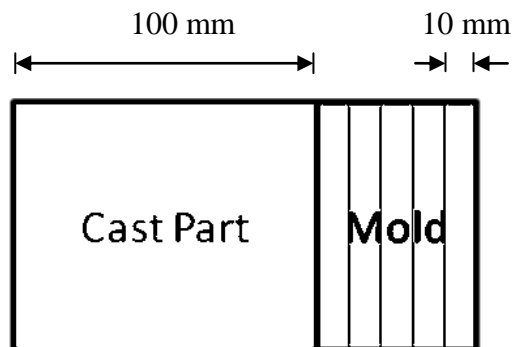
Fig. 2.2 Different layers of mould

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Consider a thin slice of material with a thickness Δx. The gradient at x is somewhat greater than x + Δx. Therefore heat conducted into the thin slice across the surface at x is greater than the heat conducted out of the slice across the surface x + Δx. Therefore energy and temperature within the slice must increase. All this can be expressed by making a mathematical statement of the conservation of energy. (Poirier et al., 1994)

$$Aq\mid_x = Aq\mid_{x+\Delta x} + A\Delta x \rho C_p \frac{\partial T}{\partial t} \qquad (2.24)$$

T=f(x)

x
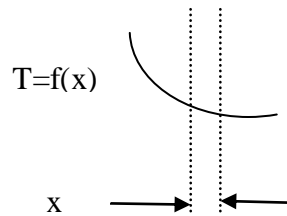
Fig. 2.3 Non linear temperature distribution in transient heat conduction

Temperature after each layer is found by using the following equation

$$T_x(t) = T_0 + (T_s - T_0)[1 - erf\frac{x}{2\sqrt{\alpha t}}] \qquad (2.25)$$

t_s is the solidification time which is calculated by using the equation

$$\frac{2Ak(T_s - T_o)}{\sqrt{\pi\alpha}}\sqrt{t_s} = \rho_m V[L + c_m(T_p - T_s)] \qquad (2.26)$$

$$t_s = \gamma(\frac{V}{A})^2 \qquad (2.27)$$

A = Area of the mould wall, which is approximately equal to the area of one of the cube face = 100×100 mm^2 or 10^{-2} m^2

V = Volume of the casting = 10^{-3} m^3

T_o = Room temperature = 300 K

T_p = Pouring temperature = 2000 K,

Pouring temperature = Liquidus temperature + Superheating = 1773 + 227 = 2000 K

k = Thermal conductivity of sand = 0.61 J/mKs

It is clear from the figure 2.3 that the temperature gradient reduces as we move farther from the interface.

For casting application it is more important to know the temperature gradient than it is to know the temperature distribution given by equation (Poirier et al., 1994). The temperature gradient is given by

$$\frac{\partial T}{\partial x} = \frac{T_i - T_o}{\sqrt{\pi \alpha t}} \exp\left[-\frac{x^2}{4\alpha t}\right] \tag{2.28}$$

Notice that the gradient varies with both x and t. At fixed time (e.g., $t=t_1$), the gradient decreases with increasing x; at a particular location, the gradient decreases with increasing time.

Rate of heat flow through the mould at any instant t is

$$\dot{Q} = -kA\frac{\partial T_x}{\partial x} \tag{2.29}$$

$$\dot{Q} = kA\frac{T_i - T_o}{\sqrt{\pi \alpha t}} \exp\left[-\frac{x^2}{4\alpha t}\right] \tag{2.30}$$

At the interface x = 0,

$$\dot{Q} = kA\frac{T_i - T_o}{\sqrt{\pi \alpha t}} \tag{2.31}$$

Total heat flow up to a certain time t_0 is

$$Q_{t_o} = \int_0^{t_o} \dot{Q}dt = 2Ak(T_s - T_o)\frac{\sqrt{t_o}}{\sqrt{\pi \alpha}} \tag{2.32}$$

General equation for total heat flow at time t

$$Q_t = 2kA\frac{T_f - T_o}{\sqrt{\pi\alpha}}\exp\left[-\frac{x^2}{4\alpha t}\right]\sqrt{t} \tag{2.33}$$

Total heat flow at the interface

$$Q_i = 2kA(T_{f\_}T_o)\sqrt{t_o}/\sqrt{\pi\alpha} \tag{2.34}$$

Total heat flow after layer 1, 2 and 3 are given by:

$$Q_1 = 2\times0.898kA(T_{f\_}T_o)\sqrt{t_o}/\sqrt{\pi\alpha} \tag{2.35}$$

$$Q_2 = 2\times0.65kA(T_{f\_}T_o)\sqrt{t_o}/\sqrt{\pi\alpha} \tag{2.36}$$

$$Q_3 = 2\times0.38kA(T_{f\_}T_o)\sqrt{t_o}/\sqrt{\pi\alpha} \tag{2.37}$$

2.5 Numerical Modelling

Solidification of castings is a non-linear transient phenomenon, posing a challenge in terms of modelling and analysis. It involves a change of phase with liberation of latent heat from a moving liquid/solid boundary. The heat is transferred from the molten metal to the environment through the solidified portion of the casting, the air gap at the casting mould interface and the mould. All three modes of heat transfer (conduction, convection and radiation) are involved. The values of physical and thermal properties, which change non-linearly over the range of temperatures involved, are not easily available and have to be obtained from detailed experiments

Finite element analysis (FEA) is a computational technique used to obtain approximate solution of the boundary value problems in engineering. Simply stated, a boundary value problem is a mathematical problem in which one or more dependent variables must satisfy differential equation everywhere within a known domain of independent variables and satisfy specific conditions on the boundary of the domain. Boundary value problems are also sometimes called field problems. The field is the domain of interest and most often represents a physical structure. The field variables are dependent variables of interest governed by the differential equations. The boundary conditions are the specified values of the field variables

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on the boundaries of the field. Depending upon the type of physical problem being analysed, the field variable may include physical displacement, temperature, heat flux and fluid velocity to name a few. In our problem the field variable is temperature being a thermal analysis (Hutton., 2004).

Finite element simulation of the solidification process involves a physical approximation of the domain, wherein the given domain is divided into small domains, called elements. Elements are basically divided into three categories

1. One dimensional element
2. Two dimensional element: triangular and rectangular
3. Three dimensional element: tetrahedral and eight node brick

The field variable inside the elements is approximated using its value at nodes. A node is a specific point in the finite element at which the value of field variable is to be explicitly calculated. The values of the field variables computed at the nodes are used to approximate the values at non nodal points (that is, in the element interior) by interpolation of the non values. For the three node triangle example, the nodes are all exterior and, at any other point within the element, the field variable is described by the approximate relation

$$\phi(x, y) = N_1(x, y)\phi_1 + N_2(x, y)\phi_2 + N_3(x, y)\phi_3 \tag{2.38}$$

Where Φ_1, Φ_2 and Φ_3 are the values of field variables at the nodes, and N_1, N_2 and N_3 are the interpolation function, also known as shape function or blending function.

Elemental matrices are obtained using variational principles and are assembled in the same way, as the elements constitute the domain. This procedure results in a set of simultaneous equations. The solution of the set gives the field's variable at the nodes.

The use of FEM enables thermal modelling of solidification close to reality taking into account

- Variation of properties with temperature
- Effect of latent heat
- Casting-mould interface heat transfer

The advantage of using FEM is the ability to handle complex boundaries and the ease in implementing boundary conditions. But this method requires considerable effort for formulation of the problem, data preparation and processing time.

2.5.1 Incorporation of air gap

For the simulation of casting solidification, the behaviour of the interface is very important as cooling rate is controlled by the interface. To model the interface, two methods are used, viz

1. Thin element for air gap
2. Coincident node technique

In this first method (*Fig. 2.4*) air gap is incorporated during simulation by introducing a virtual element of appropriate thickness for the air gap and giving an appropriate value for the interfacial heat transfer coefficient 'h' (Venkatesan et al., 2006).

In coincident node technique, the nodes of cast and mould at the interface have the same spatial coordinates.

The heat transfer from cast to the mould is incorporated through the convective heat transfer coefficient. This method offers significant savings in computer time and greater ease in modelling the mesh (*Fig. 2.5*).

Cast	Air gap	Mould
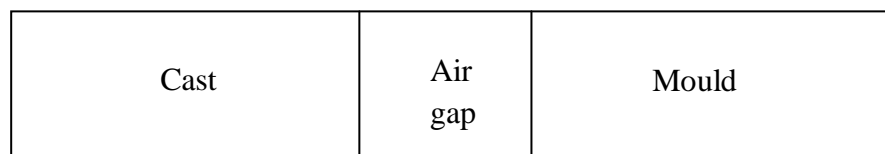
Fig. 2.4 Linear quadrilateral with thin interface element

6&7

Cast	Mould
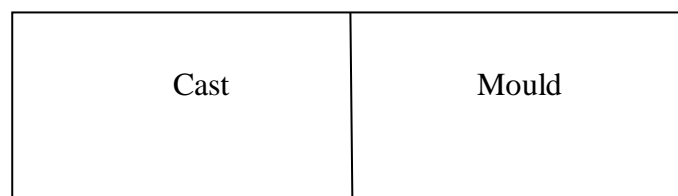
2&3

Fig. 2.5 Linear quadrilateral with coincident node

Value of h is found out experimentally. Two methods have been proposed to measure the interfacial heat transfer coefficient. One is to measure the size of the gap formed between the casting metal and the mould and convert this gap size to an appropriate heat transfer coefficient. The other method is inverse method.

From the literature review it is found that no gap is formed at the start of solidification. This is because of the adhesive forces between the liquid metal and the mould surface. However, the moment solidification starts the strength of solid layer increases. The strength is strong enough to resist the hydrostatic pressure of the molten metal which tends to push the metal shell outward. Therefore the interfacial heat transfer coefficient is rather high before the solidification temperature and drops significantly at the solidification temperatures.

Vijayaram et al., 2006, used solidification simulation of casting to calculate time-temperature data, temperature contours, hot spots location, and solidification time. The time-temperature plot explains the effect of under cooling of solidifying castings which reflects more on the inside microstructures responsible fro material properties.

Prabhu et al., 2001, investigated heat transfer at the casting/chill interface for the case of solidification of cast iron in ceramic cylindrical moulds with chill and sand block at the bottom. An inverse method of solving the one-dimensional fourier heat conduction equation was used to determine the interfacial heat flux transients and heat transfer coefficients.

Berry and Pehlke, 1988, proposed formulation of a model involving finite element approximation to the solution of the general energy equation for a given volume and the bounding surface consisting of sub surfaces governed by the boundary conditions, including specified temperature, specified flux, convective heat transfer and radiation heat transfer.

Pariona et al., 2005, compared the solidification process of sand and in mullite moulds, during 1.5 hours of solidification using numerical simulation by the finite element method. Results in 2D were obtained, such as the heat transfer, the thermal flow, the thermal gradient, the convergence control and the behaviour of temperature in different selected paths.

Lewis et al., 2000, used Finite Element modelling for optimization of feeder shape and volume of a hub casting. They investigated several geometric variants within allowable constraints using FEM and finalized the design with considerable reduction in size of feeder. Application of FEM for optimization of cylindrical feeder design for plate castings has been reported by Sun and Campbell 2003. Generally numerical modelling for solidification heat

transfer is performed to determine temperature distribution in cast metal. This is applied for identifying regions of high thermal concentration to assist in feeder design for the production of sound casting with maximum possible yield.

2.6 Conclusion from Literature Review

Literature has been reviewed on modes of heat transfer in mould, resistances offered to heat transfer, theoretical equation of solidification time and numerical simulations. The following observations are made

- Heat is transferred in metal casting during solidification through all three basic mechanisms, which are, conduction, convection and radiation.
- Conduction occurs in the solid metal and mould, convection and radiation at the interface and outer surface of mould.
- Heat flow from casting at the time of solidification experiences various resistances in its path of flow, which include
  i. The solidified metal
  ii. The metal-mould interface
  iii. The mould

- The resistance offered by metal-mould interface is due to the formation of air gap because of the shrinkage of casting during solidification.
- Air gap controls the total solidification pattern of castings and thereby affects the microstructure and quality of castings.
- Theoretical equations developed for calculating solidification time are based on certain assumptions like one dimensional conduction and constant material properties.
- The advantage of using FEM is its ability to handle complex boundaries and the ease in implementing boundary conditions.
- FEM requires much effort for formulation of the problem, data preparation and need long processing time.
- Casting solidification simulation helps us in determining the solidification time of casting, hot spot location, cooling curves, heat flux, temperature gradient, etc.

Problem Definition

3.1 Motivation

Our main aim is to maximise the productivity and yield without deteriorating the quality of cast part. The productivity and yield can be maximised by increasing the number of cavities in a mould. Increase in the number of castings however, also increases the possibility of getting defects. Therefore there is a need to create a balance between productivity and quality. In current industrial scenario, foundries lack design, methoding, and analysis experts. To overcome this, we have to take the advantage of mathematical modelling and casting simulation.

3.2 Goal and Objectives

The goal of this project is to "***develop a scientific method for optimizing casting mould cavity layout driven by thermal analysis of mould during casting solidification***"

To achieve the above mentioned goal, the following objectives are identified

1. Thermal analysis of solidification of sand casting using FEM
2. Calculate solidification time for a single cavity mould
3. Calculate optimum cavity-cavity and cavity-wall gap for multi cavity mould, using the solidification time and cavity-cavity gap relation, such that mechanical properties of casting are not affected
4. Decide the number and layout of the cavities in a multi cavity mould using optimum cavity-wall and cavity-cavity gap calculated in the previous step.
5. Verify the FEM simulation results experimentally

3.3 Research Approach

The proposed objectives will be achieved by the following steps.

- Finite Element Method planned for thermal analysis of solidification process in sand casting. The values of temperatures at different points on mould and casting are calculated. The maximum temperature of casting, which is the hot spot, is calculated and the time at which the temperature of hot spot comes to solidus temperature of the metal, is the solidification time of casting.

- A criterion is developed to find out the permissible limit, up to which the solidification time can change without affecting the mechanical properties of the cast part substantially.

- Optimal cavity-cavity and cavity-wall gap are calculated by placing the cavities in a mould in such a manner, so that the solidification time does not change by more than the permissible limit, which is calculated as per the criterion.

- Experimental analysis of solidification of casting is done by placing thermocouples in the mould. The results obtained from FEM analysis of solidification of casting are validated with the experimental results.

3.4 Scope

The scope of the work is limited to sand casting. This is because sand casting enjoys the major share as close as 80% of castings produced by weight and the widely used metals in sand castings are Ferrous and Aluminium alloys. Mould design is optimised considering only thermal constraints.

Chapter 4
Casting Solidification Simulation and Validation

This chapter discusses the methodology for simulating castings solidification using FEM, the various inputs required for solidification simulation, the output of the simulation and its validation with the experimental results.

4.1 Methodology

This section presents the methodology for performing FEM simulation on different castings.

Single cavity mould

Solidification time is calculated for simple shapes castings using ANSYS for a single cavity mould. For single cavity two types of castings are considered

- Solid cube
- Hollow cube with different thickness

Solidification time variation with mould thickness is calculated for a solid steel cube of 100 mm dimension. The thickness of mould is varied from 10 mm to 100 mm in steps of 10 mm. The solidification time is calculated for each case and graph is plotted.

The mould thickness beyond which the solidification time does not change with further increase in mould thickness is taken as the optimum mould wall thickness.

Now this wall thickness is also calculated for hollow cube casting and is further used in simulations, where cavity-cavity gap is varied keeping cavity-wall gap constant. The effect of different types of sands on solidification time of casting is also studied.

Two cavity mould

Solid Cube Cavity (100 mm): In this arrangement two solid cubes are placed in a mould and the effect of cavity-cavity gap on solidification time of casting is plotted. The mould wall thickness of the casting is the same which is calculated in the case of single cavity mould.

The cavity-cavity gap is varied from 20 mm to 60 mm in steps of 10 mm. Solidification time is calculated for different gaps and graph is plotted.

Hollow cube cavity (100 mm): In this arrangement two hollow cubes are placed in a mould and the effect of cavity-cavity gap on solidification time of casting is plotted. The mould wall thickness of the casting is the same which is calculated in the case of single hollow cavity mould. However in this case the thickness of casting is also varied, so we have taken four hollow cubes of different thickness and cavity-cavity gap is varied in each case to calculate its effect on solidification time. The thicknesses of hollow cubes and gap variation are given in table 4.1.

Table 4.1 Range of cavity-cavity gap for different thickness of casting

Thickness of cube	Cavity-cavity gap variation
20	5-20
30	10-30
35	20-30
40	20-30

The results obtained from simulating the above cases are used in calculating the optimum cavity-wall and cavity-cavity gap.

4.2 Simulation Modelling

In this section the inputs required for FEM simulation of casting are discussed. Governing equation, boundary conditions, material properties and the steps involved in simulating the solidification of casting using ANSYS are described.

This is a transient heat transfer analysis of casting process. The objective is to track the temperature distribution in the steel casting and the mould during the solidification process and to calculate the solidification time of casting. The casting is made in a cubical sand mould with a cavity of 100 mm cube.

Numerical simulation can overcome the limitation of theoretical equation derived in chapter 2 for calculating solidification time of casting. In numerical simulation the effect of interfacial

heat transfer coefficient is taken into account. The physical properties of cast metal and sand are temperature dependent and the interface temperature is not constant.

A 2-D analysis of a solid cube is performed using ANSYS (Ansys Inc., USA). The temperature profiles through the mould are drawn and the solidification time of a casting is calculated.

- Temperature dependent properties for steel are taken into consideration
- Sand physical and thermal properties are temperature dependent
- Radiation effect is neglected
- Convection at the interface is neglected
- Mould Cavity is instantaneously filled with molten metal
- Effect of latent heat is taken into account

Temperature dependent material properties like thermal conductivity and enthalpy are used to determine heat transfer during phase change. The following three steps are used to carry out the analysis

Pre-processing: Define geometry, material properties, element type and meshing
Solution: Define analysis type, ex. transient or steady state, apply thermal loads and initiate the solution
Post processing: Review the results in the form of colour coded images, graphs or tables

The general post processor is used to view results at one time step over the entire model. The time history post processor is used to determine the model over all time steps.

Solidification/melting are accompanied by the release/absorption of latent heat at the solid-liquid and solid-solid interfaces. Consequently, solidification process involves phase changes, in this case, the enthalpy method is more appropriate to describe this process, because, in this method the latent heat is inserted in the step that represents the phase transformation. Then, the general differential equation of heat conduction for the transient nonlinear state that describes this phenomenon is

$$K\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) = \frac{dh}{dt} \qquad (4.1)$$

$$h = \int \rho c dT \qquad (4.2)$$

The heat transfer mechanism by convection is established as the boundary condition

$$q = K\frac{\partial T}{\partial x}\bigg|_{x=0} = K\frac{\partial T}{\partial y}\bigg|_{y=0} = K\frac{\partial T}{\partial z}\bigg|_{z=0} = h_f (T - T_{anmbient}) \qquad (4.3)$$

Where q is the heat, K is the thermal conductivity, c is the specific heat, and ρ is the density of the material. These properties may be temperature-dependent. Then Equation 4.1 is transformed into a nonlinear transient equation. h_f is the coefficient of convective heat transfer on the mould's external surface, T is the temperature and $T_{ambient}$ is the temperature of the environment. Through equations 4.1 and 4.3 one can determine the distribution of temperature or transfer of heat during the process of solidification in casting.

4.3 Material properties used in the analysis

These are described here.

Properties of sand (Silica Sand)

Heat transfer coefficient (sand ambient) = 12 J/sec-m^2-K
Density of sand = 1600 Kg/m^3

Temperature dependent properties of sand (Table. 4.2)

Table. 4.2 Temperature dependent properties of sand (Pehlke, 1982)

Temperature (K)	Thermal conductivity (W/m-K)	Temperature (K)	Specific heat (KJ/Kg-K)
298	0.733	300	0.676
473	0.64	400	0.858
673	0.586	600	0.993
873	0.590	800	1.074
1073	0.640	1000	1.123
1273	0.703	1200	1.156

Properties of cast steel

Latent heat of steel = 272 KJ/Kg

Solidus temperature of steel = 1767 K

Liquidus temperature = 1800 K

Pouring temperature = 2000 K

Room temperature = 300 K

Density of cast steel = 7500 Kg/m^3

Temperature dependent properties of steel (Table. 4.3)

*Table 4.3 Temperature dependent properties of cast steel (Pehlke, 1982)*

Temperature (K)	Thermal conductivity (W/m-K)	Specific heat (KJ/Kg-K)	Enthalpy (J/m^3)
273	51.9	0.45	1.00×10^9
873	35.6	0.773	4.55×10^9
1073	26.0	0.931	5.23×10^9
1853	29.7	0.735	11.00×10^9

4.4 Transient Thermal Analysis of Casting using FEM

Steps Involved

1. Figure 4.1 shows a cast part enclosed in a sand mould. The two areas can be modelled in ANSYS itself or can be imported from other modelling softwares like PRO-E and CATIA.

2. Define material properties: Material properties of sand and steel are defined (*Fig. 4.2*). Material properties for both sand and steel are temperature dependent. Element type is defined as "Thermal Solid", "Quad 4node 55". We have chosen this element because the contour of the cast part in this case is linear. Had the contour been curved, we would have taken triangular element, as triangular element fits a curved domain better, and gives proper results.

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3. Meshing: Size of mesh is 1 mm (*Fig. 4.3*). Fine mesh is generally used to obtain better results. However the overall time of obtaining a solution increases with the reduction of mesh size and it requires more space in memory for calculation.

4. Apply convection on the lines of the solid model (*Fig. 4.4*). Loads applied to solid modelling entities are automatically transferred to the finite element model during solution. Heat transfer coefficient which is applied to the boundary is 12 $Wm^{-2}K^{-1}$. Temperature at the boundary is room temperature i.e. 300 K (Pariona et al., 2005).

5. Define initial condition: The mould is initially at ambient temperature of 300 K and the molten metal is at 2000 K, which is, pouring temperature (*Fig. 4.5*).
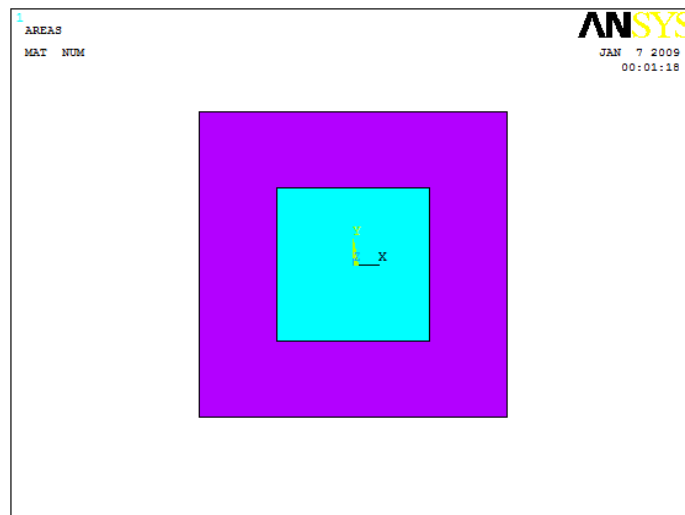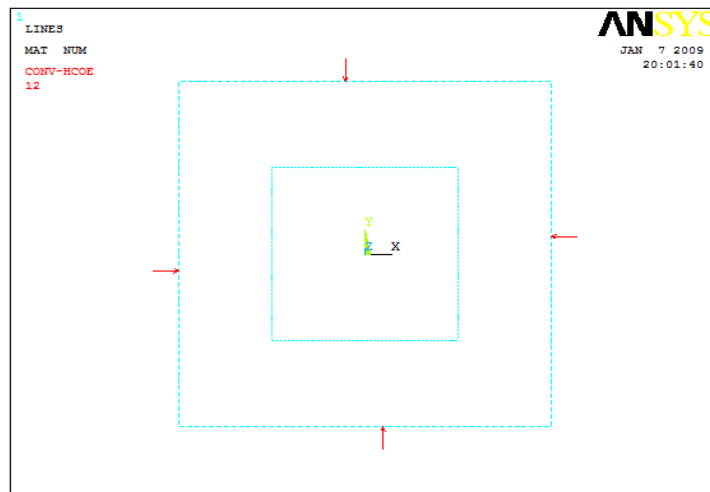

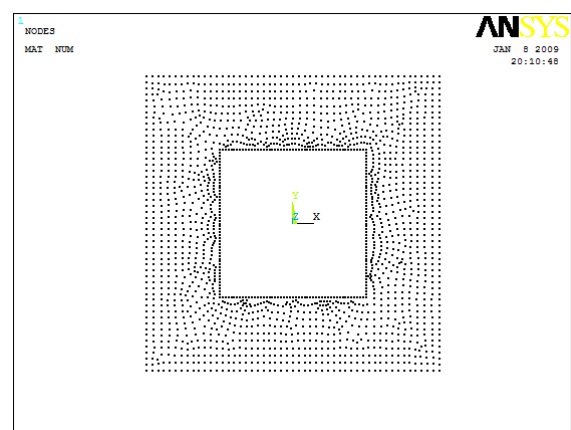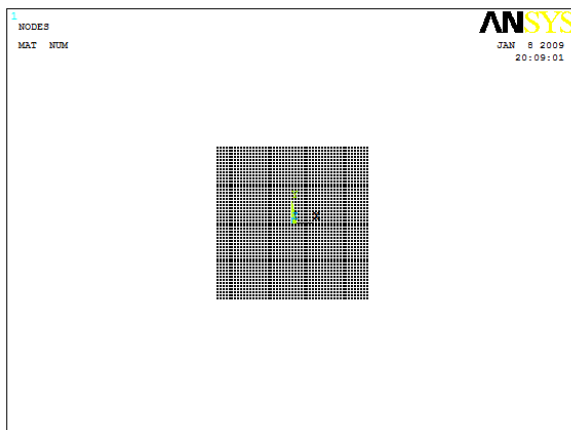*Fig. 4.1 Two dimensional model of mould with cast part inside*
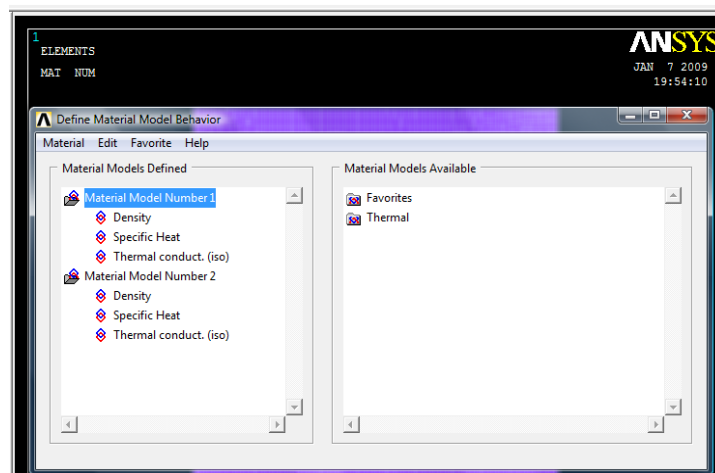
Fig. 4.2 Defining material properties

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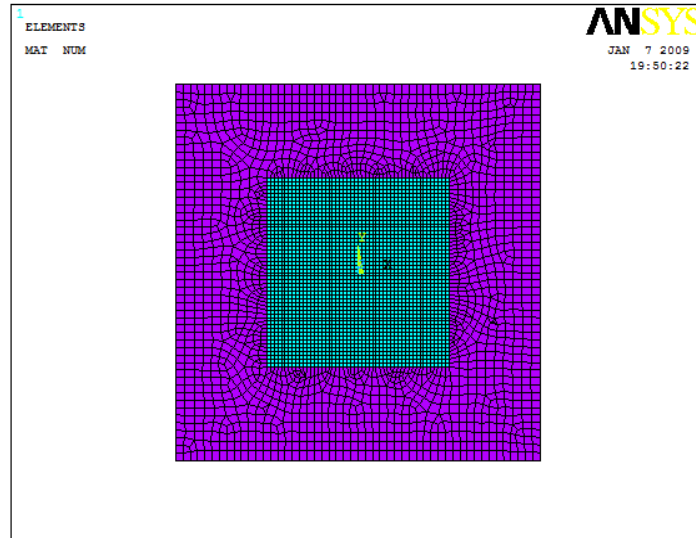
Fig. 4.3 Mesh generation

Fig. 4.4 Applying loads

Fig. 4.5 Defining initial conditions

4.5 Simulation Results

FEM simulations of solidification of simple castings are done in this section.

4.5.1 Solidification analysis of solid cube

Solidification analysis of a steel cube is done using FEM (*Fig. 4.6*). The mould wall thickness is varied and its effect on the solidification time of casting is plotted (*Fig. 4.7*). Material of casting is steel and mould is made from silica sand.
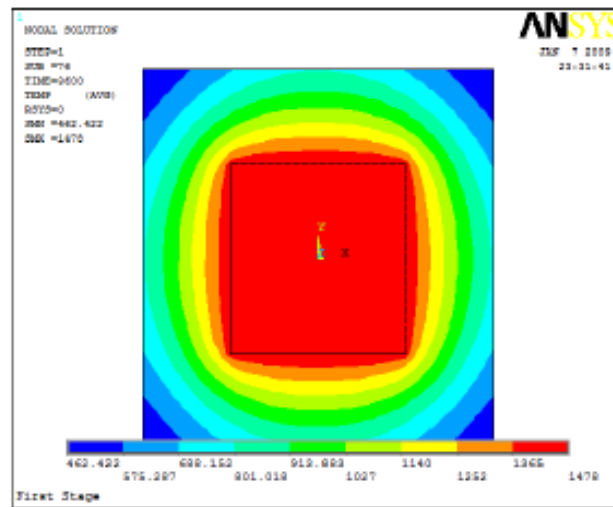

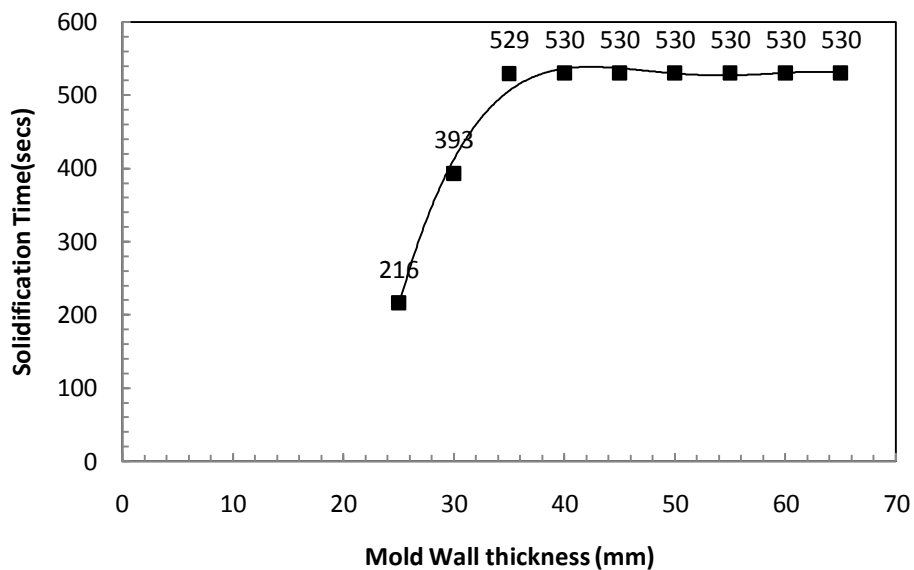*Fig. 4.6 Temperature profile in mould and casting*

*Fig. 4.7 Variation of solidification time with mould thickness*

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This analysis helps us in deciding the optimal mould wall thickness as there is no point in taking the mould wall thickness in the flat region of the curve if it is satisfying the strength criterion. In this case the optimum mould wall thickness is 35 mm. Therefore we can say that the major deciding factor while calculating optimal cavity-wall gap is the strength of the mould.

4.5.2 Solidification analysis for different types of mould sand

While designing the mould for a particular casting, solidification time of the casting helps us to decide the optimum number of cavities in a mould. Therefore every aspects of sand casting which affects the solidification time of casting is very important in optimum designing of the mould which in turn leads to higher yield, higher productivity and lesser defects.

Mould sand is a major factor which affects the solidification time of a casting. In general four types of sand are used in foundries, which are,

- Silica sand
- Zircon Sand
- Chromite Sand
- Cerabeade Sand
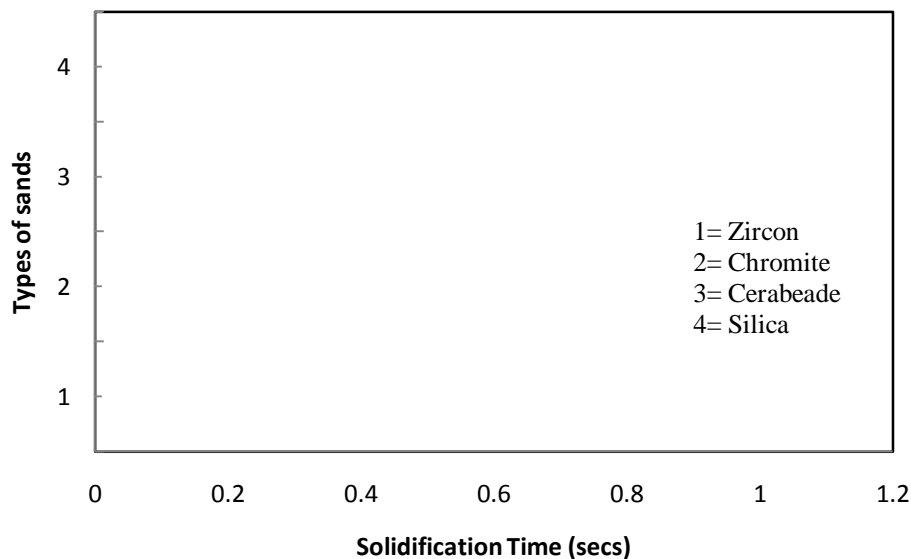
Fig. 4.8 Effect of the types of sand on solidification time of casting

It has been observed that the solidification time is minimum for zircon sand (*Fig. 4.8*). Therefore in terms of productivity zircon sand provides best alternative. However mould sand is chosen for a casting considering various requirements. Higher productivity is one of these requirements. Other requirements can be good strength, low cost, permeability, collapsibility, high fusion temperature etc. Therefore mould sand selection varies from casting to casting

4.5.3 Effect of wall thickness on solidification time of casting

Since the heat content of casting depend upon its mass therefore the solidification time of hollow casting increases with increase in its thickness. We have considered a hollow cubical casting (*Fig. 4.9*). The same effect takes place by increasing the mould thickness of mould. As discussed above that the solidification time for casting increases with increase in the mould thickness upto a certain limit and then becomes constant.

The exact effect can be seen from figure 4.10 on the next page. The solidification time increases with increase in thickness as weight of the casting is increasing.
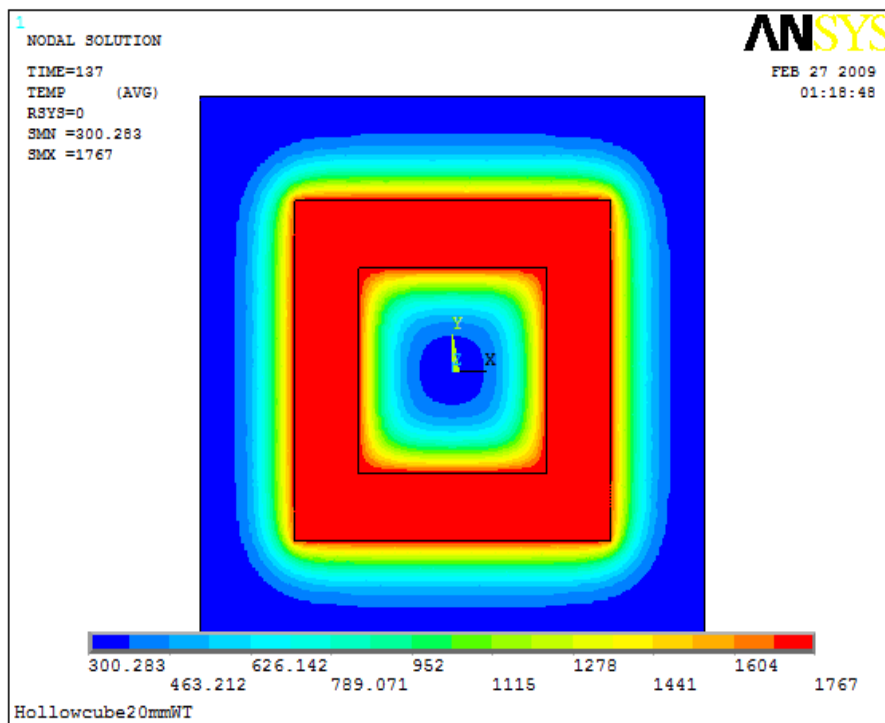
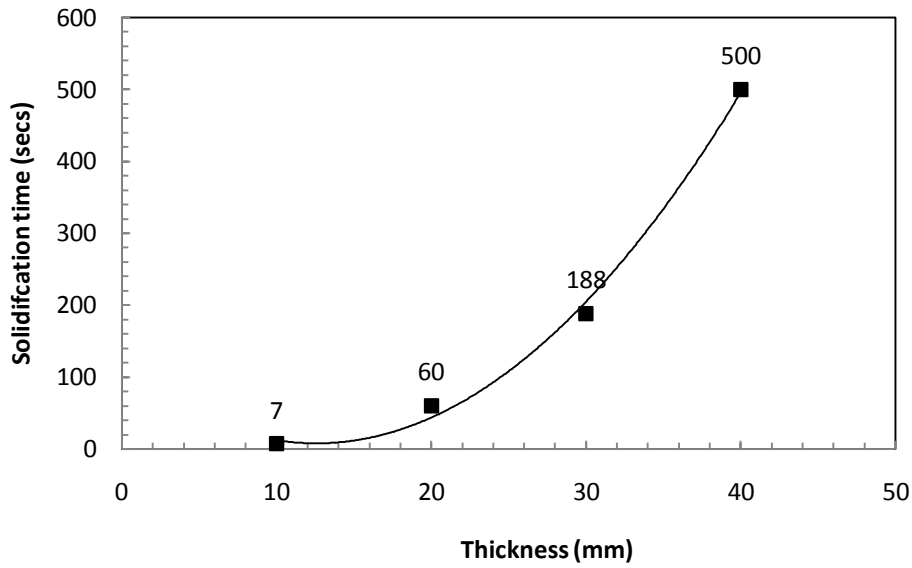*Fig. 4.9 Temperature profile in mould and casting*

Fig. 4.10 Variation of solidification time with casting thickness

4.5.4 Effect of cavity-cavity gap on solidification time of casting

Multi cavity moulds are used to produce more than one casting from a single cycle of casting operation. It is generally observed that in a multi cavity casting process the solidification time generally increases when compared to a single cavity because of restriction to the heat flow from the side of casting which is nearer to the other casting in the same mould.
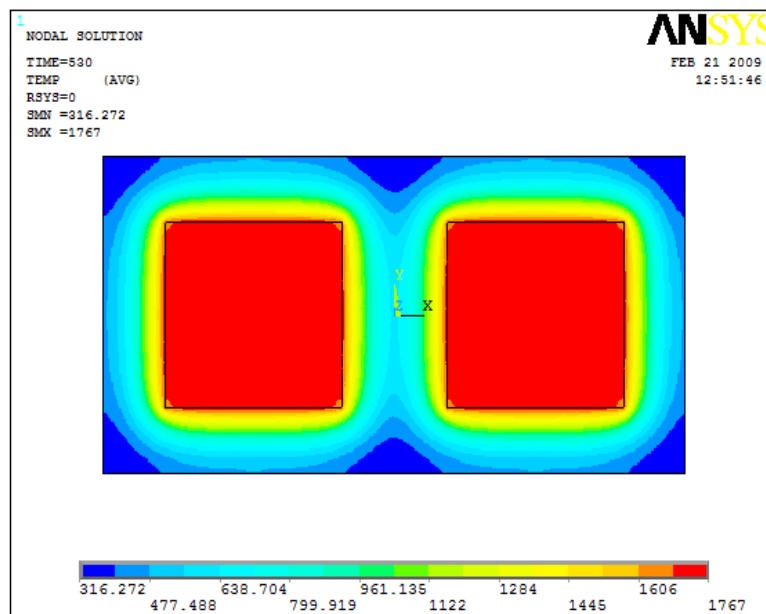

Fig. 4.11 Temperature profile in multi-cavity mould

In Figure 4.11 it can be seen that heat is being accumulated between the two castings, which in a single casting would have released without any obstruction. This increases the solidification time of casting.

Previous research and literature in casting solidification shows that lower the solidification time of a casting the better it is for the part properties and foundry productivity. The reasons are

- It increases the productivity of foundry as it is getting more number of castings in the same time.
- Lower the solidification time higher will be the chilling effect and better will be the mechanical properties.

Therefore there is a need to create a balance between the productivity and quality of casting. Packing more castings in the mould will increase the productivity but will also lead to defects due to high solidification time.
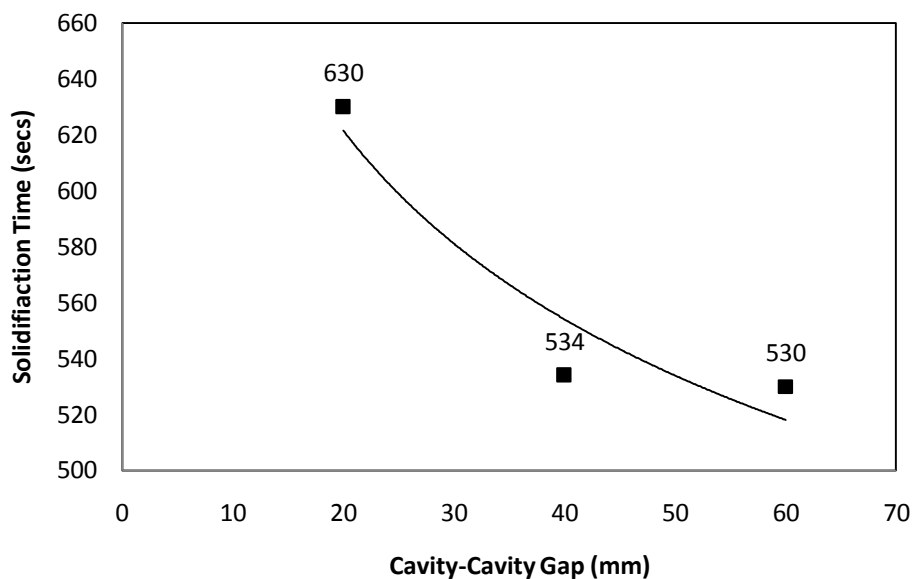
Fig. 4.12 Variation of solidification time with cavity-cavity gap

It is clear from figure 4.12 that solidification time of the casting is increasing with the decrease in the cavity-cavity gap of casting. So to optimize the cavity-cavity gap we have to find the maximum limit of the change in solidification time which we can allow to take place without affecting the quality of casting. In our simulation, gap is varied from 20 mm to 60

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mm and the solidification time is recorded. The mould wall thickness is taken as 35 mm which is the critical value calculated in the first case, that is, single cavity solid.

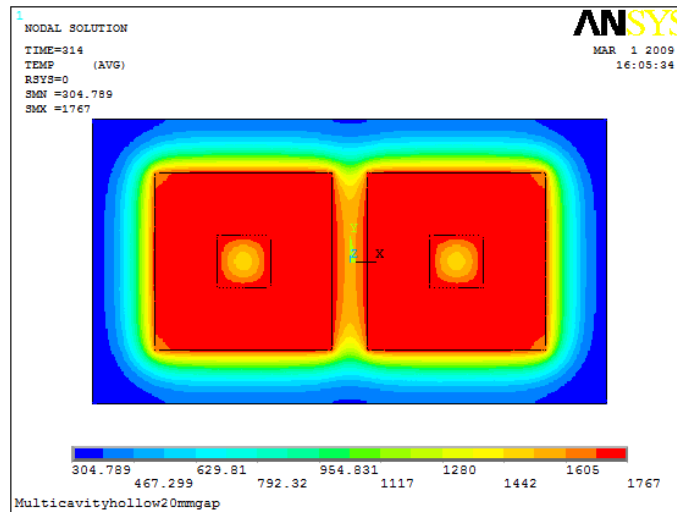### 4.5.5 Effect of cavity-cavity gap on solidification time of casting (hollow)

Fig. 4.13 Temperature profile in mould and casting

A similar analysis is done for hollow casting (*Fig. 4.13*). But it is different from the solid casting analysis because in solid casting the thickness of casting is constant and effect of thickness is not taken into account. However, here we have varied the thickness as well, and the cavity-cavity gap of casting and its effect on solidification time is noted. Figure. 4.14 - 4.17 shows the variation of solidification time of hollow cubes of different thicknesses with cavity-cavity gap.

It is seen from all the cases (*Fig. 4.14-4.17*), that the solidification time becomes constant after a certain critical value of cavity-cavity gap. So taking the cavity-cavity gap more than this critical value does not affect the solidification rate. Instead, it reduces the metal to sand ratio, which results in low productivity. The value of the critical gap is a function of casting thickness, and generally increases with increase in thickness of casting. In case 1 the solidification time does not change substantially beyond 30 mm cavity-cavity gap. In case 2 the value of this gap is 20 mm. It is 30 mm for both case 3 and case 4. From the above values one can identify that in all the cases but case 4, the value of critical gap is more or less equal to the thickness of casting.

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Case 1: 100 mm hollow cube part (35 mm Thickness) is cast in a sand mould with 30 mm mould-wall thickness. Gap is varied in steps of 10 mm (*Fig. 4.14*).

Fig. 4.14 Variation of solidification time with cavity-cavity gap (35 mm)

Case 2: 100 mm hollow cube part (20 mm Thickness) is cast in a sand mould with 30 mm mould-wall thickness. Gap is varied in steps of 10 mm (*Fig. 4.15*).
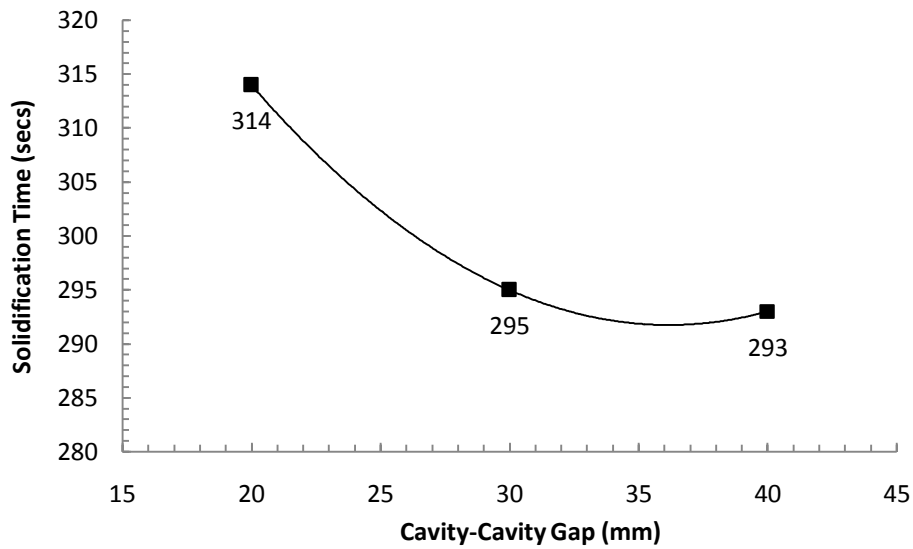

Fig. 4.15 Variation of solidification time with cavity-cavity gap (20 mm)

Case 3: 100 mm hollow cube part (30 mm thickness) is cast in a sand mould with 30 mm mould-wall thickness. Gap is varied in steps of 10 mm (*Fig. 4.16*).

Fig. 4.16 Variation of solidification time with cavity-cavity gap (30 mm)

Case 4: 100 mm hollow cube part (40 mm thickness) is cast in a sand mould with 30 mm mould-wall thickness. Gap is varied in steps of 10 mm (*Fig. 4.17*).
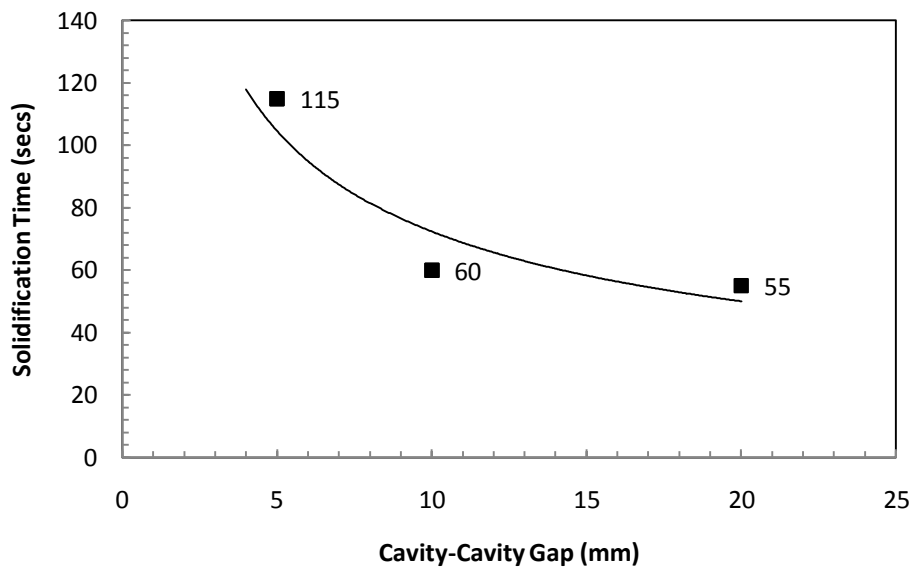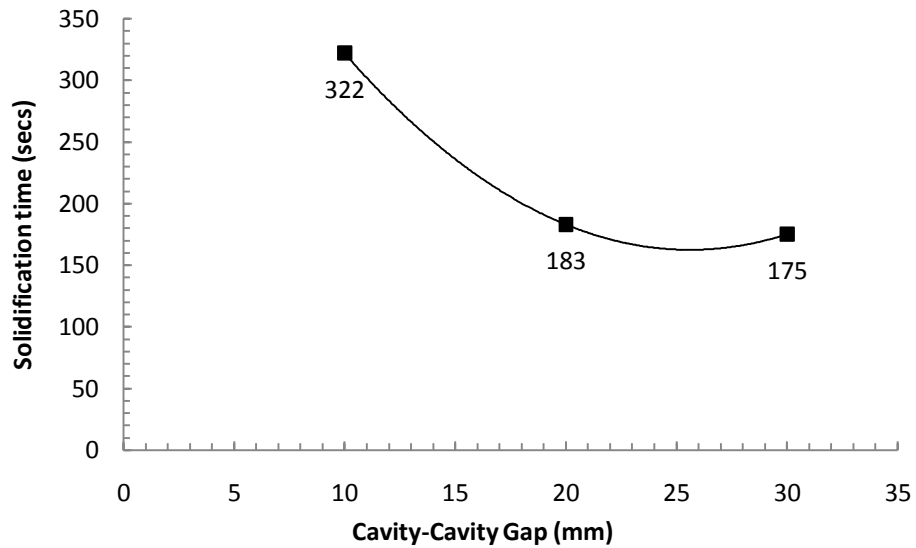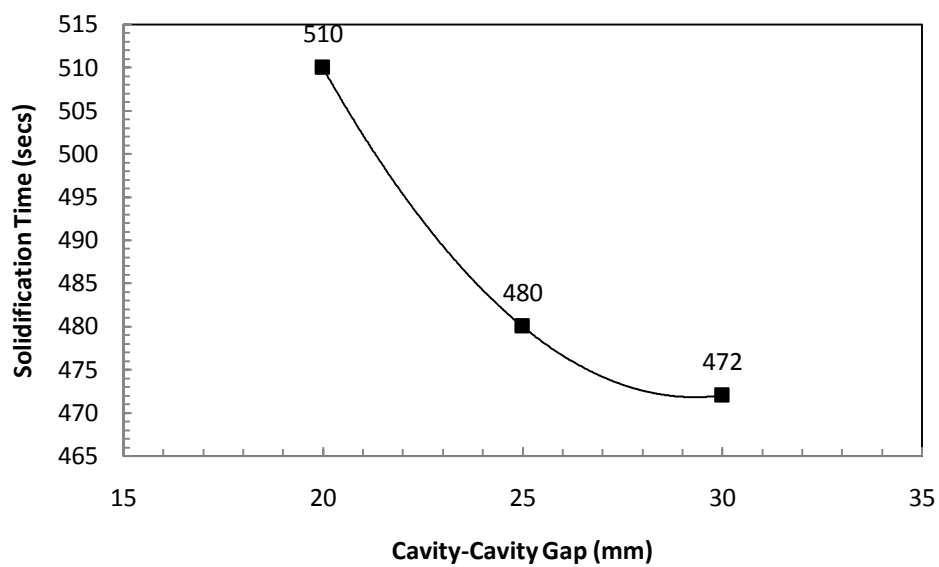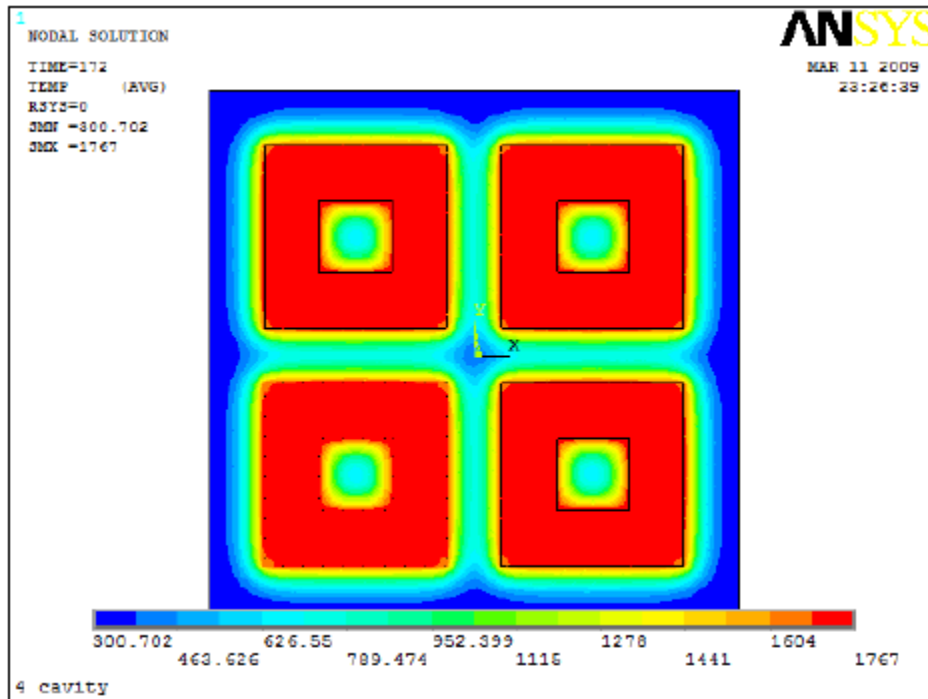

Fig. 4.17 Variation of solidification time with cavity-cavity gap (40 mm)

4.6 Verification with Four Cavity Mould

Fig. 4.18 Temp profile in mould and casting

A case of four cavities is analysed to verify the results obtained above. Four cavities are made at a 30 mm cavity-cavity gap (*Fig. 4.18*). The mould wall thickness is 30 mm. It is found that the solidification time in a four cavity mould is the same as that of a two cavity mould for the same cavity-cavity and cavity-wall gap. The simulation is done for hollow cubical casting of 30 mm thickness. The solidification time is 175 secs (*Fig. 4.16*).

4.7 3D Analysis of Casting Solidification using FEM

The basic purpose of performing this analysis is to verify the experimental results which are conducted for ductile iron casting and sand mould.

- A cast part cubical in shape of 100 mm dimension made of ductile iron is considered
- Mould is made up of silica sand
- Size of mould is 300x300x (125+125) mm.
- Temperature dependent thermal properties are considered for both metal and sand

- Interfacial Heat Transfer coefficient is taken into account
- FEM analysis software ABAQUS is used. Analysis is non-linear transient type. The casting and mould are modelled and material properties are assigned (*Fig. 4.19*).
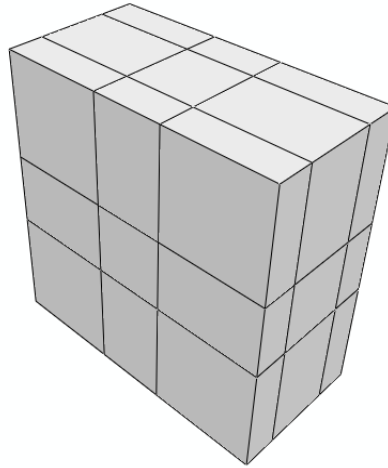
Fig. 4.19 3D model of sand mould containing casting inside

Material properties of ductile iron

These are given in table 4.4

Table 4.4 Temperature dependent material properties of ductile Iron

Temp (K)	Conductivity (W/m.K)	Temp (K)	Specific Heat (J/Kg.K)
403	38.5	373	548
608	33.5	673	586
893	25.1	873	619
1198	18.8	1073	703
1473	26.0	1473	916
1653	28.0	1653	912

Density = 7100 kg/m^3

Latent heat = 230 KJ/kg

Liquidus temperature = 1464 K

Solidus temperature =`1389 Pouring temperature = 1663 K

<u>Material properties of silica sand</u>

These are given in table 4.5

*Table 4.5 Temperature dependent material properties of silica sand*

Temp(K)	Conductivity(W/m.K)	Temp(K)	Specific Heat(J/Kg.K)
298	0.733	300	676
673	0.586	600	993
1073	0.64	1000	1123
1273	0.703	1400	1200
1473	0.7	1600	1230

Density of sand = 1520 Kg/m^3

Heat transfer coefficient for sand at ambient temp = 12 W/m^2-K

Room temperature = 300 K

Meshing is done for both mould and casting and the element size is taken as 10 mm. The element is eight node brick element (*Fig. 4.20*).
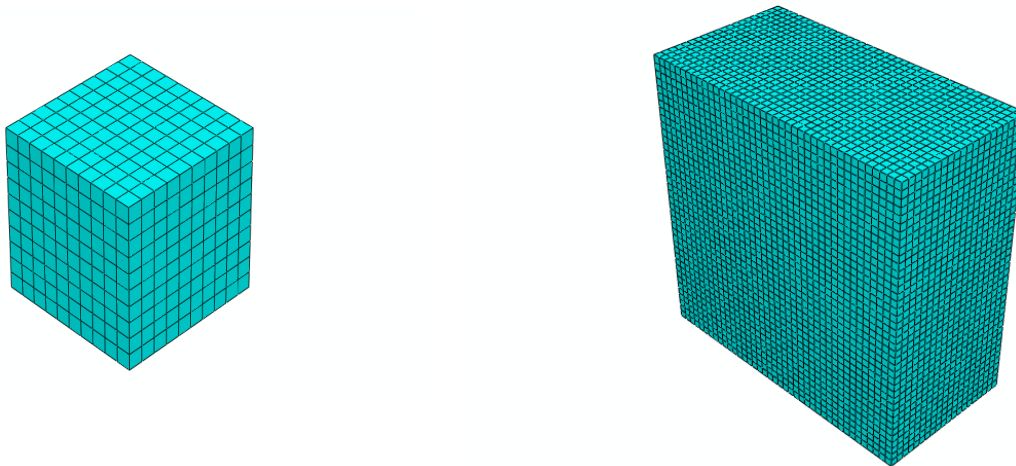
Fig. 4.20 Mesh generation of casting and mould

The boundary conditions are applied to the mould outer surface i.e. heat transfer coefficient at room temperature whose value is 12 W/m^2-K. Then initial conditions are defined for both casting and mould. The initial condition for casting is its pouring temperature 1663 K and for mould is the room temperature 300 K. The total time step for simulation is 4000 secs and increment is of 40 secs. The following results are obtained after the analysis (*Fig. 4.21*).
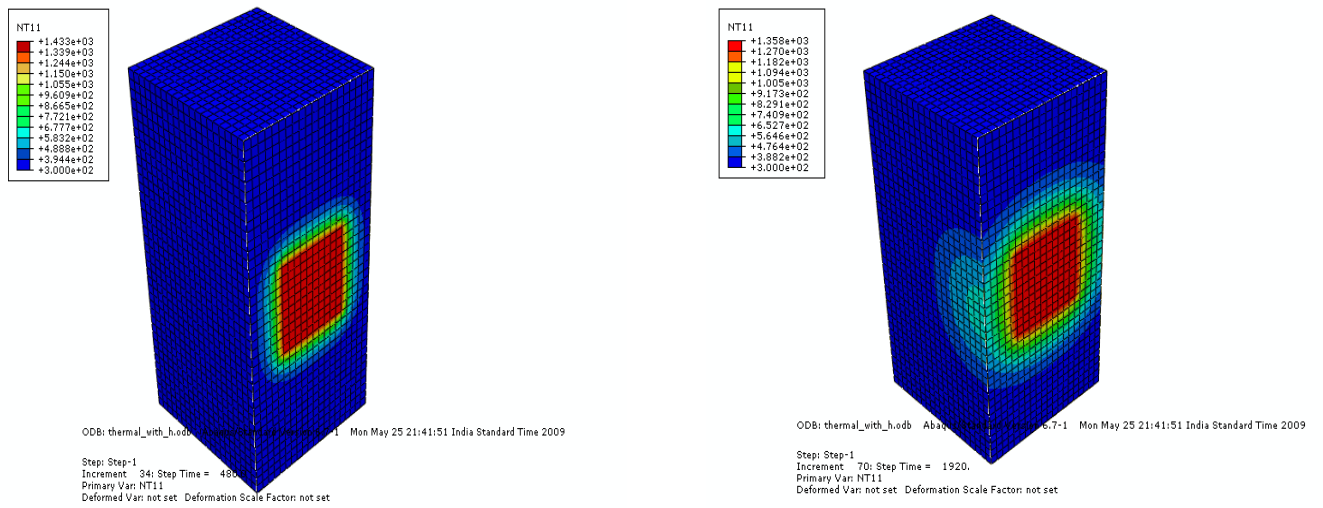
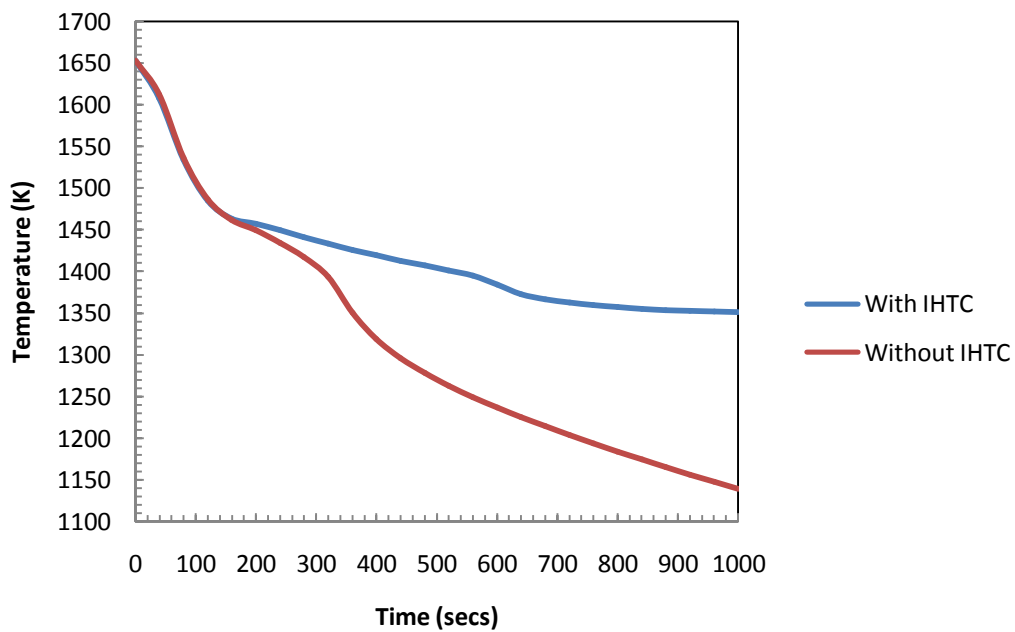*Fig. 4.21 Cooling of casting inside the mould*

Fig. 4.22 Casting cooling curves with and without IHTC

We solved the case with two conditions, which are,

- With Interfacial Heat Transfer Coefficient (IHTC)
- Without Interfacial Heat Transfer Coefficient

It is clear from figure 4.22 that the time taken by without IHTC condition is less than with IHTC condition. As we know at the time of solidification the casting generally shrinks because of which an air gap is formed at the interface of casting and mould. This air gap acts as a barrier to the heat which is flowing out of the casting. Therefore air gap will increase the solidification time of casting. Die casting shows a substantial effect of air gap because in die casting even the die also expands along with the shrinkage of casting due to high temperature. However in sand casting since the expansion of sand mould is less IHTC effect is not very prominent when compared to die casting.

Solidification time with IHTC = 600 secs

Solidification time without IHTC = 320 secs

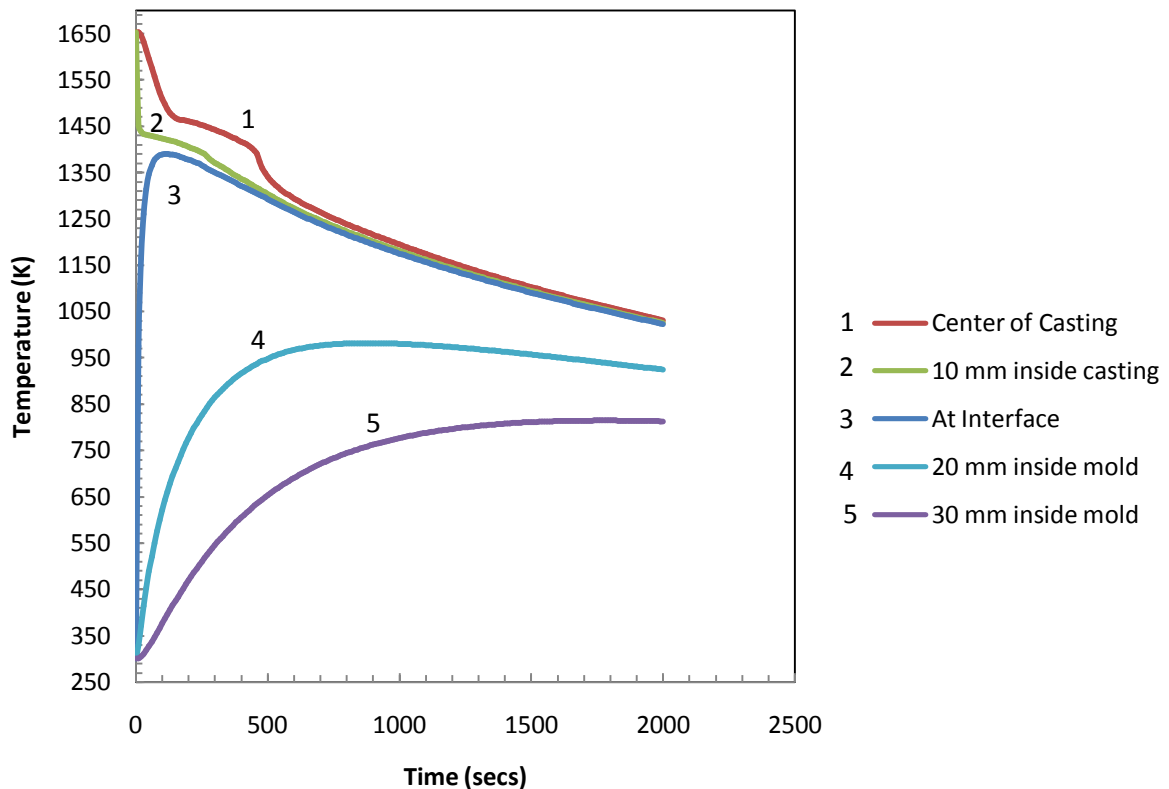The value of IHTC is 600 W/m^2-K (Prabhu et al., 2001)

Fig. 4.23 Temperature profiles at different points in casting and mould

Temperature curves are plotted for different points in casting and mould. In figure 4.23 we have plotted the cooling curves for the following point.

1. At the centre of casting (Which indicates the solidification of casting)
2. 10 mm from the interface, inside casting
3. At interface
4. 20 mm from the interface, inside mould
5. 30 mm from the interface, inside mould

It is observed from the mould temperature profile obtained from simulation that the outer temperature of mould does not change and remains at room temperature till solidification. From the simulation it is found that the temperature of the mould outer surface or rather outer half of the mould does not change till solidification. Therefore the boundary condition at the outer mould where heat transfer coefficient is given does not have any effect on the final results.

4.7.1 Solidification of ductile iron

Ductile iron undergoes a net expansion during solidification. The volume of the solidified iron at the end of solidification (before solid contraction) is greater than the volume of the liquid poured into the mould.

When molten metal is poured in the mould it undergoes liquid contraction from the superheat temperature to the liquidus. This contraction is very predictable since it is dependent on the coefficient of expansion of the alloy. Eutectic expansion follows the liquidus. The remaining liquid transforms into austenite and graphite. Expansion always occurs during the eutectic transformation and it is very significant. This is because all of the carbon in the liquid iron minus the carbon dissolved in the austenite precipitates as graphite during the eutectic. Graphite has a much higher specific volume compared to iron causing the expansion that is observed. The density of graphite is 2.2 g/cc compared to 7 g/cc for that of iron.

After the above discussion it is clear that air gap formation in the case of ductile iron is not substantial so the value of interfacial heat transfer coefficient is very high in it. Even the trend of change of IHTC does not follow the general rule. Therefore the results obtained from experiments are more close to the simulation results in which IHTC is neglected.

4.8 Experimental Verification

Experiments are conducted to validate the results for one case each for single cavity and multi cavity. The validation is done by installing thermocouples at different points in the mould and comparing them with the results obtained from simulations for the same cases. Experiments were conducted at SS Foundries, Ichalkaranji. The cast metal used in experiments is ductile iron and the mould material is silica sand.

The temperature is recorded with the help of a 16 station data logger which can measure temperature at 16 points simultaneously. A data logger (data recorder) is an electronic device that records data over time or in relation to location either with a built in instrument or sensor or via external instruments and sensors

Type K thermocouple is used to perform the experiments. It is the 'general purpose' thermocouple. It is low cost and, owing to its popularity, it is available in a wide variety of probes. Thermocouples are available in the -200°C to +1200°C range. It is composed of a positive leg of 90% nickel, 10 chromium and a negative leg of 95% nickel, 2% aluminium, 2% manganese and 1% silicon.

Mould box of size 300×300×250 mm is used for the experiment and a cavity of 100×100×100 is made using a wooden pattern having proper allowances. Weights are placed on the mould after pouring as ductile iron has the property of expanding during solidification which can lead to leakage or bursting of mould if mould does not have adequate strength

In multi cavity mould, temperatures are calculated at different points. In this case as shown in figure, the thermocouple are inserted from the cope i.e. top of the mould. It will solve the problem of the leakage through the parting surface. However the accuracy of placing the thermocouples at the exact position may not be high here.

Temperatures at different points are measured after an interval of 5 secs. Experiment is run for a duration of 1.5 Hrs. Temperature curves are plotted for particular points with the help of the data retrieved from data logger. Figure 4.24 and 4.25 show the set up of the experiment. Figure 4.26 and 4.27 show the position of thermocouples in the mould. In figure 4.28, temperature values recorded by using thermocouples are plotted with respect to time.
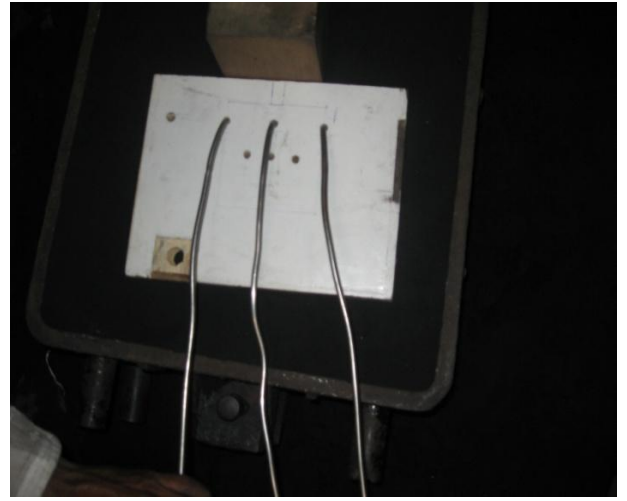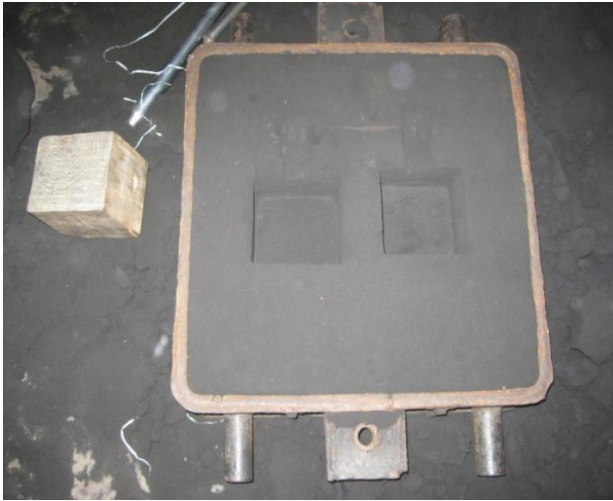
Fig. 4.24 Multi cavity mould inserted with thermocouples
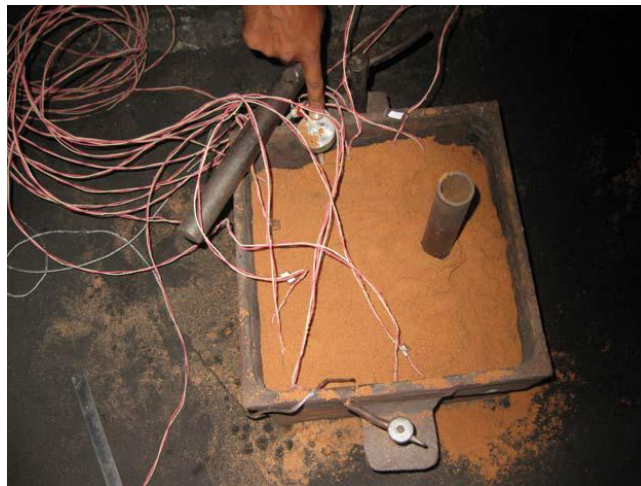
Fig.4.25 Layout of thermocouple placed in mould (single cavity)
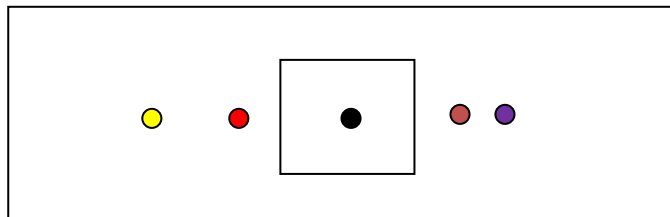
Fig.4.26 Position of thermocouple in the mould (front view)
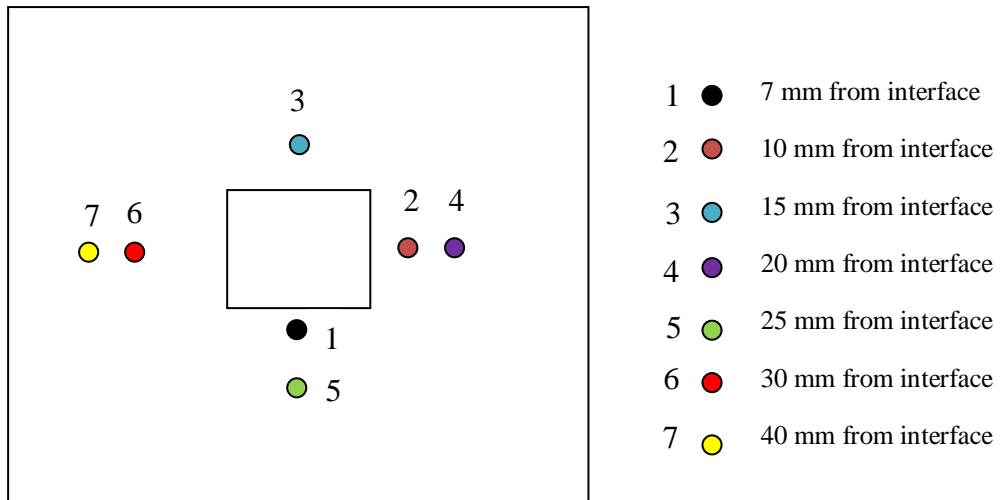
Fig.4.27 Position of thermocouple in the mould (top view)
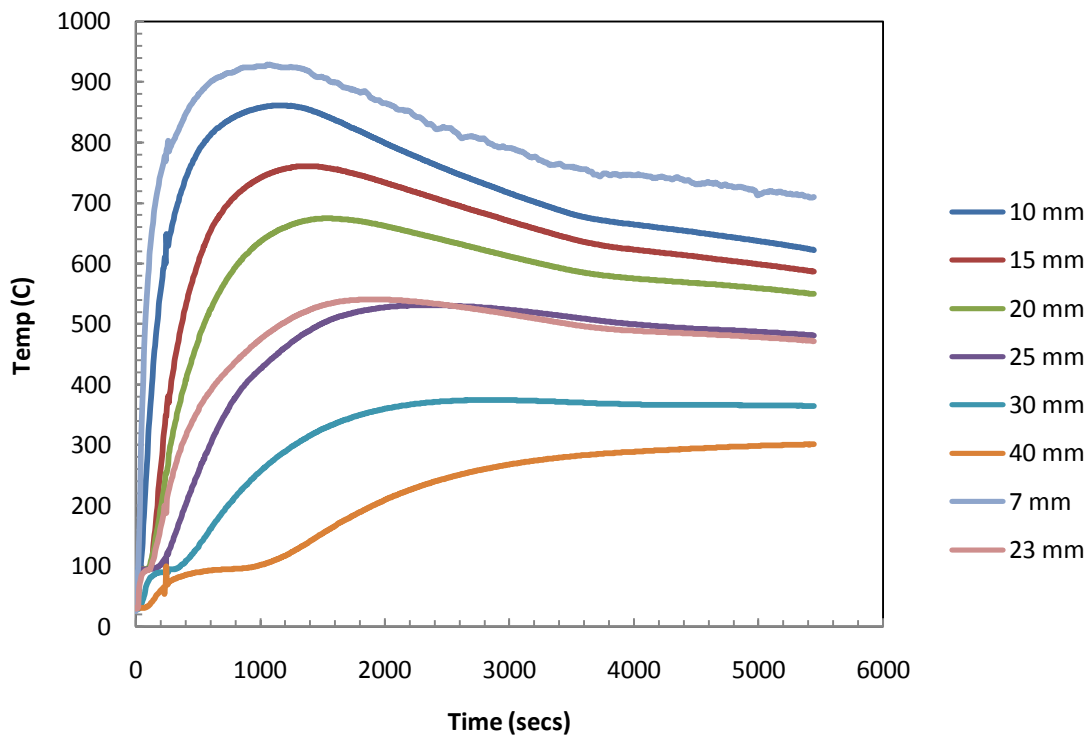
Fig. 4.28 Temperature curves in the mould (experimental)

4.9 Validation with Experimental Results

The simulated results of casting solidification are compared with the experimental results in this section.

a) Comparison of temperature curve obtained by simulation and experiment at 30 mm inside mould

Fig. 4.29 Comparison of simulated and experimental results (30 mm)

b) Comparison of temperature curve obtained by simulation and experiment at 20 mm inside mould

Fig. 4.30 Comparison of simulated and experimental results (20 mm)

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c) Comparison of temperature curve obtained by simulation and experiment at 10 mm inside mould

Fig. 4.31 Comparison of simulated and experimental results (10 mm)

The temperature variations with respect to time are plotted for points which are at 10 mm, 20 mm and 30 mm distance from the interface and lie inside the mould. Figure 4.29 shows the comparison of temperature profile gener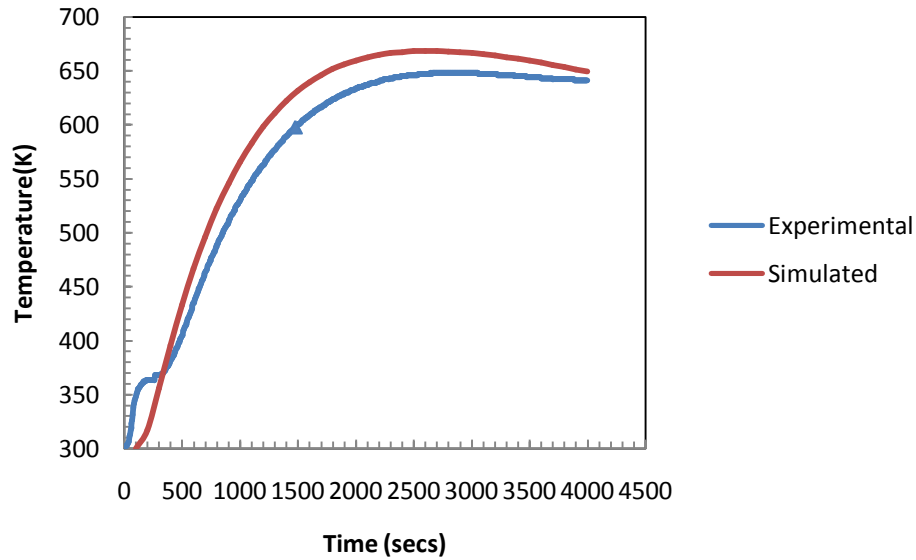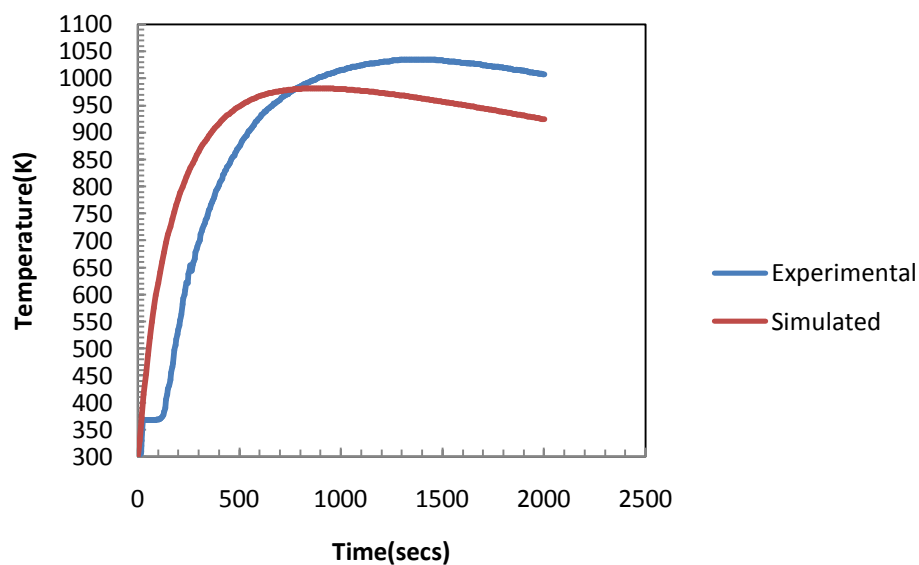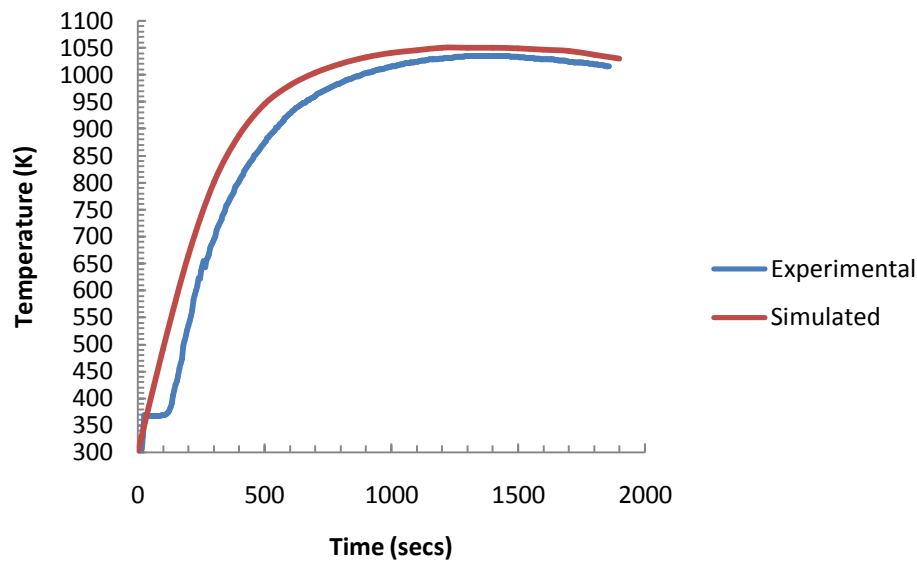ated by simulation and experiment at 30 mm inside the mould. Figure 4.30 and 4.31 show the same comparison for 20 mm and 10 mm respectively.

An almost good match is obtained between simulated and experimental values for the three points. The major reasons for some difference between experimental and simulated results are as follows:

- The locations of the thermocouples placed in the mould are not very accurate, as the movement of sand while ramming displaces the thermocouples wire from their proper positions.
- The difference between the material properties used in simulation and the actual properties of the material used in experiment.
- The effect of air gap at the interface is neglected in simulation.
- The diameter of the thermocouple wire itself is 2 mm. So it is not possible to measure the exact temperature values at specific points like 10mm, 20 mm, 30 mm. etc.

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4.10 Summary of the Chapter

In this chapter solidification analysis of casting is done using FEM. Effect of cavity-cavity gap on casting solidification time is studied. The simulated results are experimentally validated with a brief explanation of the experimental set up.

Chapter 5

Optimum Cavity-Cavity Gap and Layout Optimization

The results obtained from the simulations and the discussions in the previous chapters are utilized to optimise the cavity-cavity gap and generate a flow chart for optimizing the cavity layout in a mould. Sand to metal ratio is calculated for different types of mould for comparison.
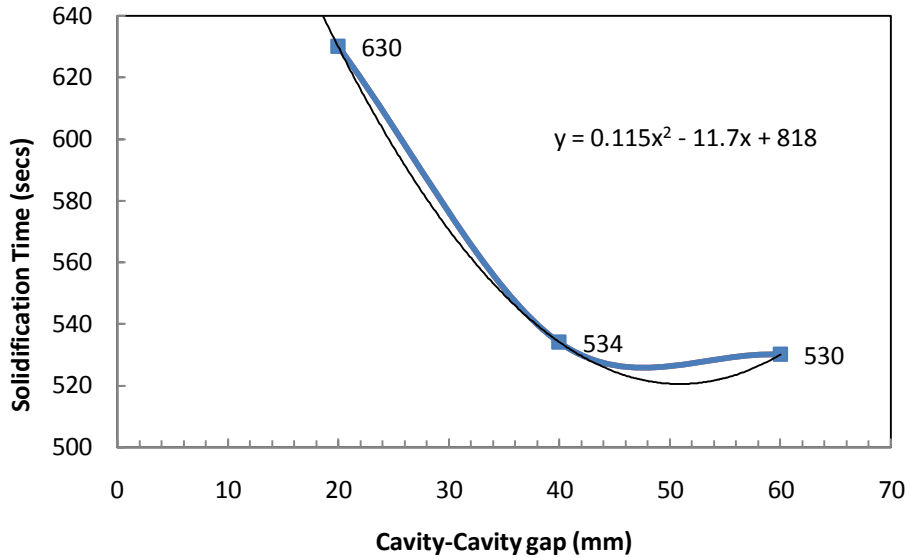
5.1 Optimal Cavity-Cavity Gap Calculation

Optimum value of cavity-cavity gap is calculated using simulation results and applying solidification time criterion. We have considered that if a casting is manufactured in a multi cavity mould and its solidification time does not increase by more than 10% of the solidification time of the same casting in a single cavity mould, then the mechanical properties of casting remain almost unaffected and are similar to the properties of single cavity mould casting.

Case 1: Multi Cavity Solid

It has been found out from simulation that solidification time of a 100 mm cube casting in a single cavity mould casting is 530 secs. But when the same casting is manufactured in two cavity mould and the cavity-cavity gap is reduced the solidification time increases as indicated in the figure 5.1. Now we know that we can allow only an increase of up to 10 % of the solidification time in a single cavity. Therefore 53 secs increase in solidification time will lie in permissible limit. Then the total solidification time will be 530 +53 = 583 Secs.

To obtain the equation of the trend of increase in solidification time with reduction in cavity-cavity gap we tried to fit different curves in the above graph, like exponential, logarithm, polynomial, linear, power etc. and found that polynomial best fit the curve, as can be seen from the graph below (*Fig. 5.1*).

Fig.5.1 Curve fitting (polynomial order 2)

$$y = 0.115x^2 - 11.7x + 818 \qquad (5.1)$$

Here y axis represents the solidification time, and

x represents the cavity-cavity gap.

Using this equation we can calculate the optimal cavity-cavity gap. The allowable solidification time is 583 secs. Therefore value of y is 583 secs. Now solving for x we will get x = 27 mm.

It means the minimum value of cavity-cavity gap for this case should be 27 mm, without introducing defects and diminished properties.

Case 2: Multi Cavity Hollow

The same approach is applied for multi cavity hollow casting. A 100 mm hollow cube part (35 mm thickness) is cast in a sand mould with 30 mm mould-wall thickness. Gap is varied from 20 mm to 40 mm as shown in figure 5.2. For a single cavity the solidification time is 290 secs. Therefore the allowable solidification time will be 320 secs in the case of multi cavity mould, assuming 10% increase in solidification time is permissible.
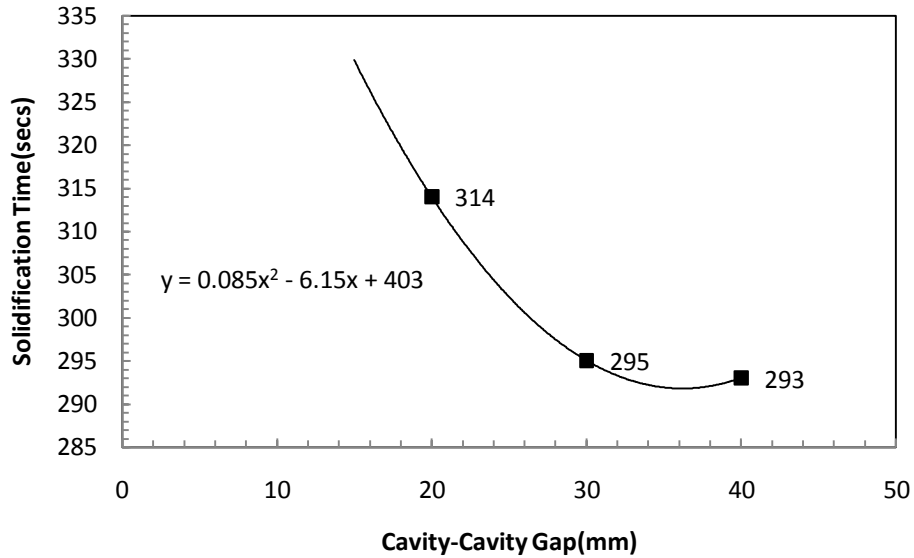
Fig.5.2 Curve fitting (Polynomial order 4)

An order 4 polynomial is fitted which best suits the above trend.

The equation for the curve is

$$y = 0.085x^2 - 6.15x + 403 \qquad (5.2)$$

Here y represents the solidification time

x represents the cavity-cavity gap

For y = 320 secs

After solving the equation 5.2 for y = 320 secs, we get x = 19, which is also indicated from the figure 5.2. Therefore the minimum cavity-cavity gap for this case is 19 mm.

Using the same procedure value of cavity-cavity gaps for castings of different thicknesses are also calculated. The values calculated are then plotted with casting thickness (*Fig 5.3*)
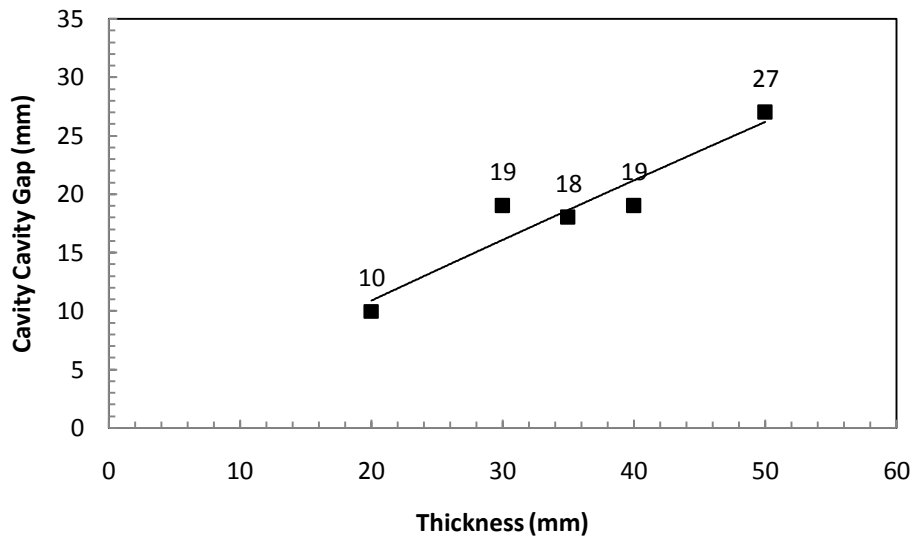
Fig. 5.3 Relation of cavity-cavity gap with thickness of casting

5.2 Metal to Sand Ratio Criteria

The optimal value of cavity–cavity obtained from the simulation of multi cavity solid casting is used to calculate the metal to sand ratio for different layouts i.e. single cavity, two cavity and four cavity.

It is found that the optimal cavity-wall gap for a solid cube casting of 100 mm dimension is 35mm from figure 4.7. The minimum cavity-cavity gap obtained above for multi cavity solid cube casting of 100 mm dimension is 27 mm (Fig. 5.1). Using these gaps we calculated metal to sand ratio (mould yield) for different types of moulds and their layouts. Comparison is done on the basis of mould yield. Higher the mould yield better is the productivity.

Single Cavity (*Fig. 5.4*)
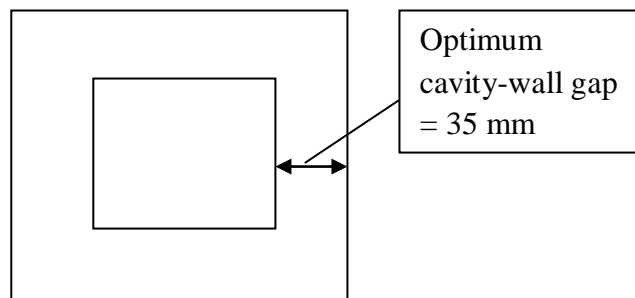
Fig. 5.4 Single cavity mould

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Cavity volume = 1000000 mm^3

Mould volume = 4913000 mm^3, Metal weight = 7.87 Kg

Sand volume = 3913000 mm^3, Sand weight = 6.26 Kg

Mould Yield = Metal Weight/Sand Weight = 1.25

a)   Two Cavity Mould (*Fig. 5.5*)
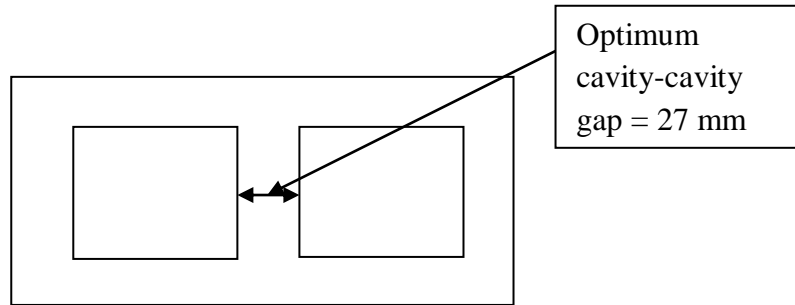
Fig. 5.5 Layout of two cavity mould

Cavity volume = 2000000 mm^3

Mould volume = 8583300 mm^3, Metal weight = 15.74 Kg

Sand volume: = 6583300 mm^3, Sand weight = 10.55 Kg

Mould Yield = Metal Weight/Sand Weight = 1.49

b)   Four Cavity Mould

Layout 1: Four cavities are arranged in the manner shown in the figure 5.6
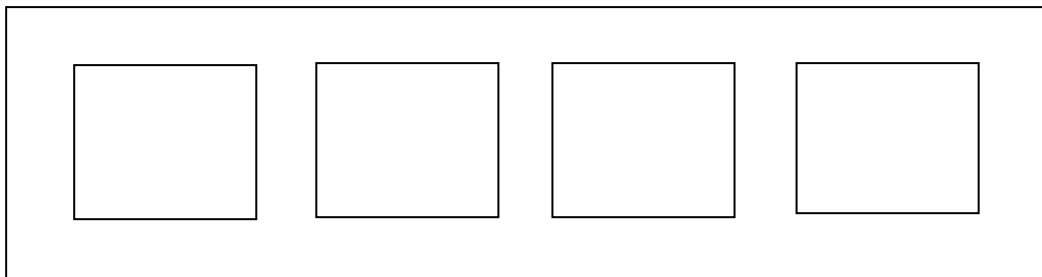
Fig. 5.6 Layout of four cavity mould (4×1)

All the four cavities are along a straight line.

Cavity volume = 4000000 mm^3

Mould volume = 15923900 mm^3, Metal weight = 31.48 Kg

Sand volume = 11923900 mm^3, Sand weight = 19.07 Kg

Mould Yield = Metal Weight/Sand Weight = 1.65

Layout 2: Four cavities are arranged in the manner shown in the figure 5.7
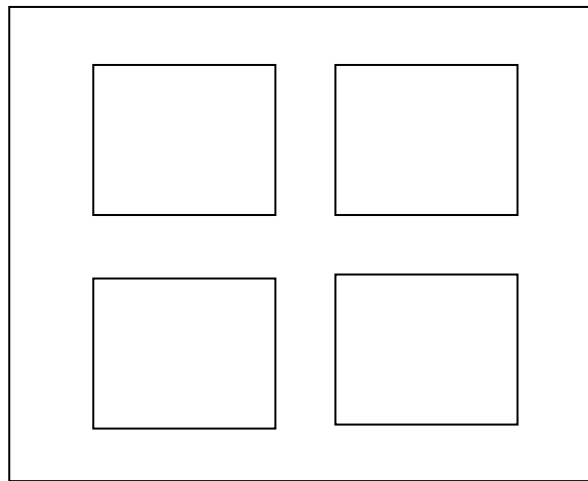
Fig. 5.7 Layout of four cavity mould (2×2)

Cavity volume = 4000000 mm^3

Mould volume = 14995530 mm^3, Metal weight = 31.48 Kg

Sand volume   = 10995530 mm^3, Sand weight = 17.59 Kg

Mould Yield = Metal Weight/Sand Weight = 1.78

Table.5.1 Variation of mould yield with number of cavities in a mould

Number of cavities	Mould yield
1	1.25
2	1.49
4 (4×1)	1.65
4 (2×2)	1.78

As seen from table 5.1 that the metal to sand ratio increases with the increase in the number of cavities in a mould for same cavity-cavity and cavity-wall gap. The metal to sand ratio also gets affected by the layout of cavities in a mould.

5.3 Flow Chart for Optimizing Mould Design

Fig. 5.8 Flow chart for mould cavity layout optimization

5.4 Case Study

To implement the results obtained in the previous chapters, a real life casting is taken and simulated to find its solidification time. The solidification time calculated from simulation is compared with the solidification time obtained from the relation of solidification time and thickness of casting which is developed for the case of simple castings in chapter 4.

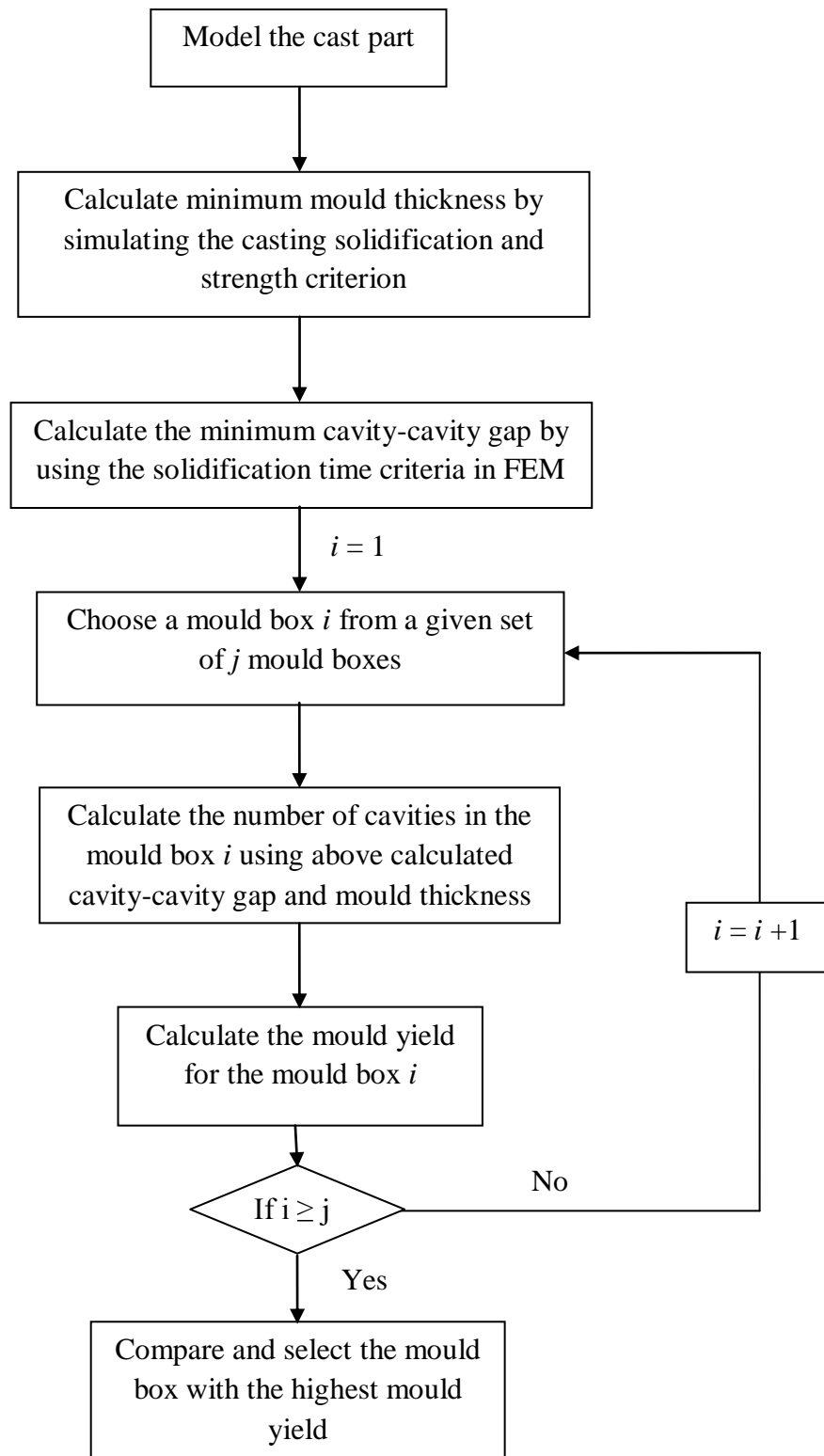A cast part of stepped rectangular section with a hole in the centre is simulated in ABAQUS (*Fig. 5.9*). The material of the part is cast steel and the material of the mould is silica sand. The dimensions and shape of the part are shown on the next page. The material properties of cast steel and sand are same as taken in the previous cases of steel casting simulation (Table 4.3) in chapter 4. The analysis is 3D non linear transient type.

From FEM analysis using ABAQUS (*Fig. 5.10*), we get solidification time of the casting, τ_s = **141 secs.**

As we know the values of optimum cavity-cavity gap for hollow cube castings of different thicknesses. It is found that the optimum cavity-cavity gap for hollow casting is around half of the thickness of the casting for most of the cases (*Fig. 5.3*)

In this case study the thickness of casting is 30 mm. So according to our results the optimum cavity-cavity gap should be around 19 mm (*Fig. 5.3*). It means that, if we take cavity-cavity gap as 19 mm then the solidification time of the castings in a two cavity mould should not increase by more than 10% of the solidification time of the single cavity mould casting, which is 141 secs. Now to verify this we have simulated the casting solidification for a two cavity mould in ABAQUS (*Fig. 5.11*) and found the solidification time = 151 secs.

Now,
Solidification time for a single cavity is 141 secs
10 % of 141 = 14.1
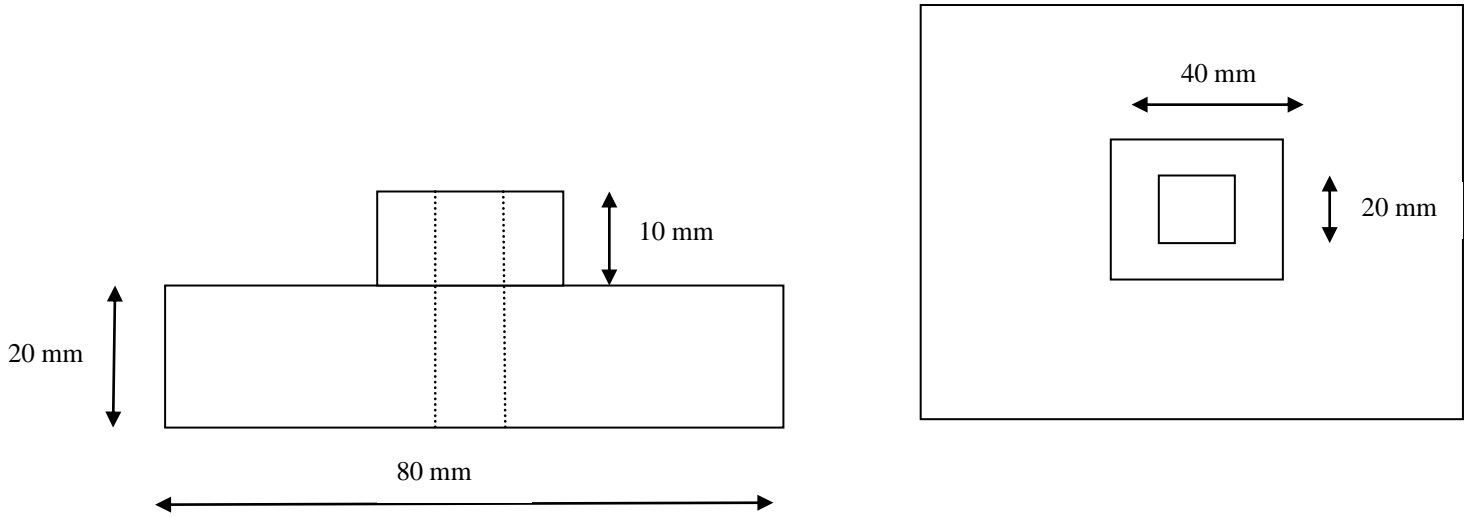141 + 14.1 = 155.1 secs (Permissible limit of solidification time)

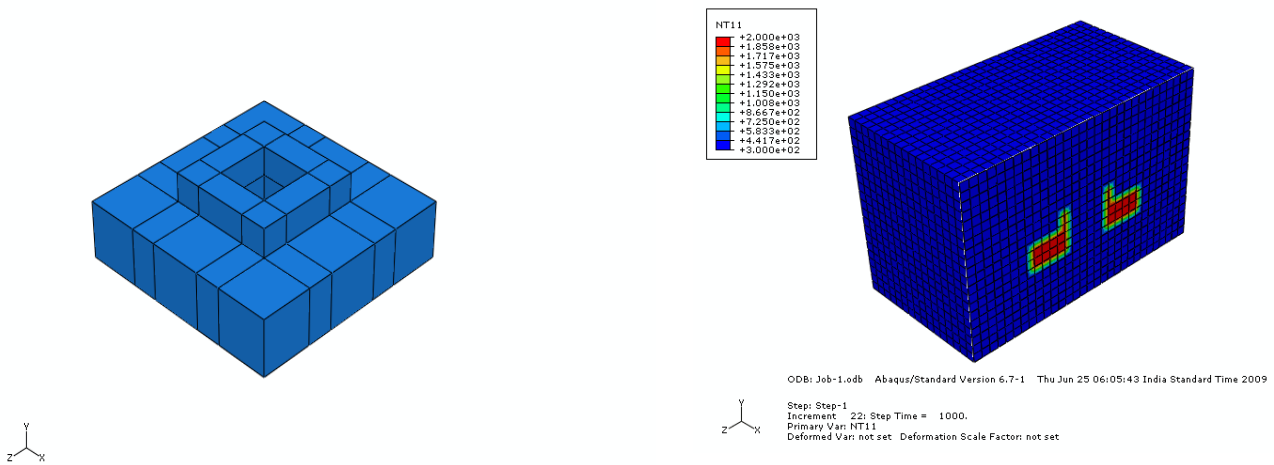*Fig. 5.9 Front view and top view of the casting*

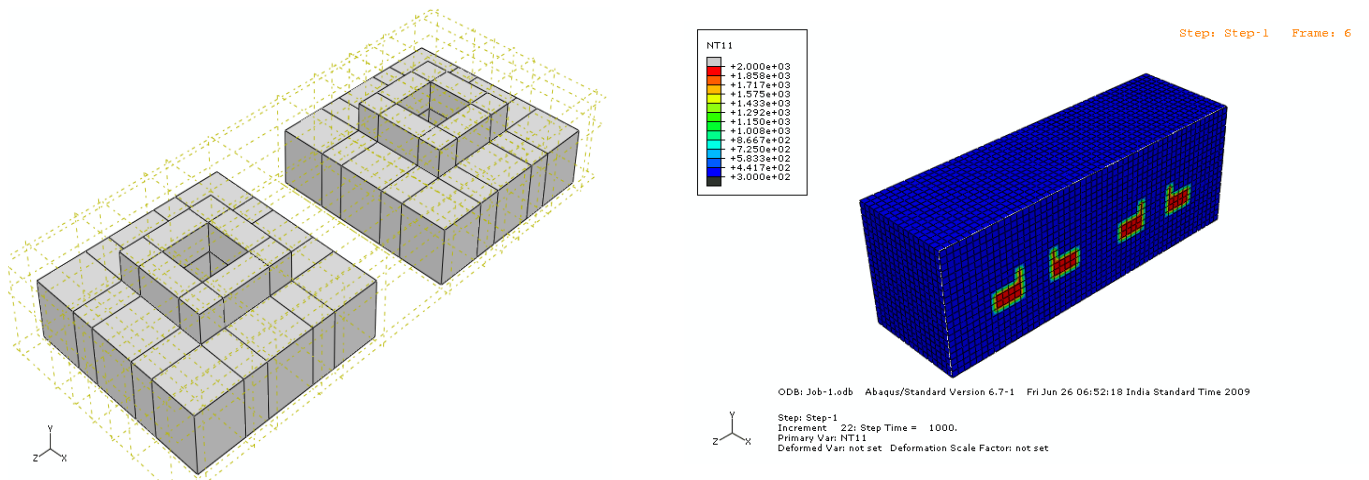*Fig. 5.10 Single cavity layout (3D)*

Fig. 5.11 Two cavity layout (3D)

Solidification time calculated from simulation is 151 secs, which lies in the permissible range, which is less than 155.1 secs. Therefore it satisfies the solidification time criterion.

So, the minimum cavity-cavity gap for this part is 19 mm.

Now we have to select a mould box from a given set of mould boxes, which gives us the maximum metal to sand ratio. To decide this we first have to decide the optimum number of cavities in a given mould box, which depends on the minimum cavity-cavity gap and cavity-wall gap. Then we calculate the metal to sand ratio for each mould box, and the one which has the maximum metal to sand ratio will be selected.

To accommodate a single cavity in a mould box, the sum of the length of casting and the mould wall thickness on both sides of casting should be less than or equal to the dimension of the smallest edge of the mould box. For two cavity, the sum of the length of two castings, cavity-cavity gap and the mould wall thickness on both sides of casting should be less than or equal to the dimension of the edge parallel to which the two cavities are formed.

Above conditions can be generalised by the following equation

$$n \times l + (n-1) \times G_{cc} + 2 \times G_{cw} \leq L \qquad (5.3)$$

n = Number of cavities

l = Length of the cavity

G_{cc} = Cavity-cavity gap

G_{cw} = Cavity-wall gap

L = Length of mould box

It means that n number of castings of length l, cavity-cavity gap G_{cc} and cavity-wall gap G_{cw} can be accommodated in a mould box of length L, if it satisfies the equation 5.3. The same equation can be applied to calculate the number of cavities along the breath of the mould box. But in this case the value of cavity-cavity gap and cavity-wall gap will change if the breadth of the casting is different from its length.

We have considered four mould boxes of different sizes, which are as follows:

1. 200×200×150
2. 300×300×200
3. 450×450×300
4. 550×500×350

The dimensions are in mm. These are standard sizes of moulds which are widely used in foundries.

Minimum cavity-cavity gap and cavity-wall gap are 19 mm and 30 mm respectively for the cast part. All the castings are arranged in a single plane inside the mould box, that is, castings are not placed one above the other.

The following results are obtained by using the equation 5.3 for each mould box (Table. 5.2). It is found that mould box 3 has the maximum metal to sand ratio value, hence it is the best option.

Table 5.2 Metal to sand ratio for different types of mould boxes

Mould box	Mould box size	Number of cavities	Cavity layout	Metal volume (mm^3)	Sand volume (mm^3)	Metal to sand ratio
1	200×200	1	1×1	132000	5868000	0.022
2	300×300	4	2×2	528000	17472000	0.030
3	450×450	16	4×4	2112000	58638000	0.036
4	550×500	20	5×4	2640000	93610000	0.028

5.5 Summary of the Chapter

A methodology to calculate the optimum cavity-cavity gap for a casting is discussed. A flow chart is presented to optimize the cavity layout in a mould. A case study is solved using the same methodology.

Conclusions

Summary of the work done and its future scope is discussed in this chapter.

6.1 Summary of Work

To improve the yield and productivity of sand casting process, a simulation based method to optimize mould cavity layout has been developed. The work is summarised here

- Metal casting being one of the major process in manufacturing of metal parts, therefore there is need to improve the process in terms of productivity and yield to maximize profit and reduce lead time.
- Yield is increased in a casting process by increasing the number of cavities in a mould.
- Number of cavities in a mould depends upon the cavity-wall and cavity-cavity gap.
- Lesser the cavity-cavity and cavity-wall gap more the number of cavities can be accommodated in a given mould.
- At the same time reducing cavity-cavity and cavity-wall gap increases the solidification time of the casting. Increase in solidification time affects the grain size of casting and diminishes its mechanical properties.
- Thus, there is a need to develop a balance between the number of castings in a mould and the permissible amount of increase in solidification time due to increase in number of castings.
- The permissible limit of increase in solidification time of casting in multi cavity mould is taken as 10% of the solidification time for a single mould. If the solidification time changes more than this, then it is assumed to affect the mechanical properties of casting.
- Solidification time for solid and hollow cube castings in a single cavity mould is calculated using FEM. The trend of increase in solidification time due to decrease in cavity-cavity gap is studied for same castings in a multi cavity mould.
- Curve is fitted to the trend obtained from the above step and equation of the curve is determined.

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- The equation produced is used to calculate the cavity-cavity gap corresponding to the permissible limit of solidification time. It means the permissible value of solidification time gives us the optimal value of cavity-cavity gap in multi cavity mould.

- Results obtained from transient thermal analysis using FEM are verified experimentally.

- Thermocouples are placed in mould and temperature is recorded at different points in the mould using a data logger and then temperature curves are plotted for these points.

- These temperature curves are compared with the temperature curves generated by simulating solidification of same casting in ABAQUS.

- Effect of interfacial heat transfer coefficient (IHTC) on the solidification process of casting is studied. It is found that solidification time decreases with the increase in IHTC.

6.2 Future Scope

The future work which can be carried out in this project is as follows

- The effect of IHTC can be studied in more detail and its temperature dependent values can be incorporated in the simulation as boundary condition.

- Calculating cavity-cavity gap and cavity-wall gap using strength criteria.

- It is useful to extend the scope of the project to other casting processes and materials. Currently it is limited to ferrous sand castings.

- More complex castings can be considered.

References

- Alawode A.J., " Mechanical properties of cast aluminium rods under varied foundry sand sizes and mould preheat temperatures," *Journal of Engineering and Applied Sciences*, Vol. 3, No. 8, pp. 626-633, 2008.

- ASM, "Casting design handbook," *American Society for Metals*, 1962.

- Beeley P., "Foundry Technology," *Butterworth-Heinemann,* 2001.

- Beffel M.J., Wilkes J.O., R.D. Pehlke., "Finite element simulation of casting processes," *AFS Transactions*, Vol. 94**,** pp. 757–764, 1986.

- Berry J.T. and Pehlke R.D., "Modeling of solidification heat transfer," *ASM Handbook Casting, American Society of Metals*, Vol. 15, pp. 858-866, 1988.

- Bennett B.A.V., "Adaptive numerical modelling of natural convection, conduction, and solidification within mould cavities," *Numerical Heat Transfer, Part A: Applications*, Vol. 51**,** pp. 313-342, 2007.

- Bralla J.G., "Design for manufacturability handbook," *McGraw Hill, New York*, 1999.

- Campbell J., "Casting practice-10 rules of casting," *Elsevier Publications,* 2004.

- Campbell J., "Castings," *Butterworth-Heinemann,* 1991.

- Chen Y. and Taek Y., "Analysis of solidification in sand and permanent mould castings and shrinkage prediction," *International Journal of Machine Tools Manufacturing*, Vol. 30, No. 2, pp. 175-189, 1990.

- Ghosh A. and Mallik A.K., "Manufacturing science," *East-West Press, India*, 2004.

- Hutton D., "Fundamentals of finite element analysis," *McGraw Hill, New York,* 2004.

- Joshi D., "Casting solidification simulation for feedability analysis," *Recent Trends in CAE,* 2008.

- Kulkarni S.N. and Radhakrishna K., "Evaluation of metal-mould interfacial heat transfer during the solidification of aluminium -4.5% copper alloy castings cast in CO_2 −sand molds," *Material science-Poland*, Vol. 23, No. 4, pp. 821-838, 2005.

- Lewis R.W., Huang H.C., Usmani A.S. and Tadayon M.R., "Solidification in castings by finite element method," *Material Science and Technology*, Vol. 6**,** pp. 483-488, 1990.

- Lewis R.W., Manzari M.T. and Gethin D.T., "Thermal optimisation in the sand casting process," *Engineering Computations*, Vol. 18, pp. 392-416, 2001.

- Lewis R.W., Manzari M.T. and Ranking R.S., "Casting shape optimisation via process modelling," *Material and Design*, Vol 21, pp. 381-386, 2000.

- Lewis R W. and Roberts P M., "Finite element simulation of solidification problems," *Applied Scientific Research*, Vol. 44, pp. 61-92, 1987.

- Mahapatra M.M., Datta G.L., Pradhan B. and Mandal N.R., "Three-dimensional finite element analysis to predict the effects of SAW process parameters on temperature distribution and angular distortions in single-pass butt joints with top and bottom reinforcement," *International Journal of Pressure Vessels and Piping*, Vol. 83, pp. 721-729, 2006.

- Naik H.B., "Finite element simulation of solidification of castings," *Recent Trends in CAE,* 2008.

- Pariona M.M. and Mossi A.C., "Numerical simulation of heat transfer during the solidification of pure iron in sand moulds," *Journal of the Brazil Society of Mechanical Science and Engineering*, Vol. 27, No. 4, pp. 399-406, 2005.

- Pehlke R.D., Jeyarajan A. and Wada H., "Summary of thermal properties for casting alloys and mold materials," *University of Michigan, Ann Arbor*, 1982.

- Poirier D R. and Poirier E J., "Heat transfer fundamentals for metal casting," *Second Edition, Minerals, Metals, & Materials Society, USA,* 1994.

- Prabhu K.N. and Griffiths W.D., "Casting/Mould interfacial heat transfer during solidification of cast iron," *49th Indian Foundry Congress*, pp. 68-77, 2001.

- Prabhu K.N., Chowdary B. and Venkatraman N., " Casting/Mould thermal contact transfer during solidification of Al-Cu-Si Alloy(LM 21) plates in thick and thin moulds," *Journal of Material Engineering and Performance*, Vol 14, No. 5, pp. 604-609, 2005.

- Ravi B., "Metal casting- computer aided design and analysis," *Prentice Hall India*, *Third Edition*, 2005.

- Ravi B., Creese R.C. and Ramesh D., "Design for casting - a new paradigm to prevent potential problems," *AFS Transactions*, Vol 107, 1999.

- Ravi B., "Knowledge-based casting design," *Proceedings of 62nd World Foundry Congress*, Philadelphia, USA, pp. 23-26, 1996.

- Ravi B. and Shrinivas M.N., "Casting solidification analysis by modulus vector method," *International Journal of Cast Metals Res*, Vol 9, pp. 1-7, 1996.

- Samonds M. and Morgan K., "Finite element modelling of solidification in sand castings employing an implicit-explicit algorithm," *Applied Mathematical Modelling*, Vol 9, pp. 170-174, 1985.

- Sun L. and Campbell J., "Optimised feeder design for Al-12Si, Alloy," *AFS Transaction*, pp. 101-106, 2003.

- Sun H.C. and Chao L.S., " Analysis of interfacial heat transfer coefficient of green sand mould casting for aluminium and tin-lead alloys by using a lump capacitance method," *Journal of Heat Transfer*, Vol 129, pp. 595-600, 2007.

- Thomas B.G., Samaraeskera I.V. and Brimacombe J.K., "Mathematical model of the thermal processing of steel ingots," *Metallurgical Transaction,* Vol 18, pp. 131-147, 1987.

- Venkatesan A. and Gopinath B., "Simulation of casting solidification and its grain structure prediction using FEM," *Journal of Materials Processing Technology,* Vol 165, pp. 10–15, 2005.

- Venkatesan A. and Rajadurai A., "Effect of air-gap on casting solidification," *AFS Transaction, USA*, pp. 191-199, 2006.

- Vijayaram T.R., Hamouda A.M.S., Ahmad M.H.M. and Sulaiman S., "Numerical simulation of casting solidification in permanent metallic moulds," *Journal of Material Processing technology*, Vol 178, pp. 29-33, 2006.

Additional Web References

1. http://www.jintaninternational.com/ArticleFiles/Sand%20casting.htm, accessed on 2nd March 2009.

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