PREDICTION OF BLOWHOLES IN SAND CASTING

M.Tech Project Report

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Abstract

Blowholes are one of the major casting defects caused due to evolution and entrapment of gases during casting process. This project aims to develop a systematic approach for blowhole prediction in sand casting based on available knowledge, experience of experts in this area and mathematical modeling of physical phenomenon taking place during mold filling.

The initial study involved studying blowholes, principle of their formation, causes and remedies and preparing a knowledge base. The focus is on large size blowholes occurring in sand casting. Mathematical equations were derived for gas pressure developed during mold filling and for temperature drop of metal during mold filling (considered layer-by-layer). These were implemented in a software developed for blowhole prediction. The user inputs include the 3D model of the casting (in the form of STL file) and relevant pouring parameters. The layer-by-layer filling of mold cavity is simulated, accompanied by computation and display of instantaneous temperature of metal and gas pressure developed in the mold cavity. The software was tested on two industrial components – grey iron bush and pulley, and it could successfully predict blow hole formation in both cases, as seen in practice. This enables the user to experiment with parameters like pouring height, vent dimensions, number of vents, number of ingates and sand volume to minimize the occurrence of blowholes by design.

This is perhaps the first attempt of its kind in blow hole modeling and prediction. The work can be further enhanced by considering metal turbulence, metal splashing , dynamic shocks during pouring and back pressure of gases on metal front, to predict the exact location of blow holes, and to extend the work to other types of gas-related defects.

Keywords: Blowholes, casting defects, 3-D modeling, process simulation.

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Nomenclature

ρ = density of the metal, kg m^{-3}

ρ_{gas} = density of gas = density of air = 1.30 kg m^{-3}

$\rho_{hydrogen}$ = density of hydrogen, kg m^{-3}

$\rho_{nitrogen}$ = density of nitrogen, kg m^{-3}

σ = Stefan Boltzman's constant = 5.67 $\times$ 10^{-8} W m^2 ^{o}K^{-4}

τ_i = time for which gas is passing through mold walls at instant i, sec

k_{mold} = thermal conductivity of the mold, W m ^{o}K^{-1}

C_m = specific heat of the molten metal kJ/kg – ^{o}K

C_f = coefficient of friction between metal and mold wall

A_i = cross sectional area of mold cavity at instant i

$A_{surface\_i}$ = surface area of mold in contact with metal layer dl at instant i

A_{mold_i} = area of the mold in contact with the metal at instant i, m^2

A_{ingate} = area of ingate, m^2

A_1 = area of vent at entry point of the gas, m^2

c_d = coefficient of discharge = $c_c \times c_v$

c_c = coefficient of contraction = 0.7 to 0.8

c_v = coefficient of velocity = 0.98

dl = small liquid metal thickness under consideration in m^2

f = permeability of sand, m^{3}N^{-1}s^{-1}

h_r = radiation coefficient of convection W/m^2-^{o}K

h = coefficient of convection between metal and surrounding gases W/m^2 - ^{o}K

H_l = loss of pressure head due to venting, m

l_i = distance traveled by the metal from bottom of the mold (entry point) at instant i,m

m_i = mass of the liquid metal under consideration at instant i in kg

P_{gas_i} = pressure of evolved gases at instant i, N m^{-2}

$P_{metallostatic}$ = the metallostaic pressure, N m^{-2}

P_{mold_i} = total pressure inside the mold at instant i, N m^{-2}

P_{air_i} = air pressure at instant i, N m^{-2}

$P_{evo\_hydrogen}$ = pressure due to evolution of hydrogen, N m^{-2}

$P_{evo\_nitrogen}$ = pressure due to evolution of nitrogen, N m^{-2}

$\Delta P_{permeability}$ = pressure drop of gas due to sand permeability at instant *i*

$\Delta P_{venting}$ = reduction in gas pressure due to escaping of gases through vents at instant *i*

ΔP_{escape_i} = total reduction in gas pressure due to escaping of gases at instant *i*

Q_{T1} = heat lost by conduction through bottom of the mold

Q_{T2} = heat lost by convection and radiation from top of the metal layer

R = specific gas constant, J/kg-^oK

$R_{hydrogen}$ = specific gas constant for hydrogen, J/kg-^oK

$R_{nitrogen}$ = specific gas constant for nitrogen, J/kg-^oK

$R_{moisture}$ = specific gas constant for steam, J/kg-^oK

R_{binder} = specific gas constant for gas due to binder, J/kg-^oK

$R_{additive}$ = specific gas constant for gas due to additives, J/kg-^oK

T_a = atmospheric temperature in ^oK

T_p = pouring temperature of metal in ^oK

T_m = melting temperature of metal in ^oK

T_{mold} = temperature of the mold ^oK

ΔT_i = small change in temperature of layer *dl* at instant *i,* in ^oK

$t_{effective}$ = thickness inside mold wall upto which hot molten metal is heating sand contents

V_i = volume of mold cavity at instant *i,* m^3

$V_{hydrogen}$ = volume of hydrogen, m^3

V_{gas_i} = volume of gas at instant *i*, m^3

$V_{nitrogen}$ = volume of nitrogen, m^3

V_{mold} = volume of mold, m^3

$V_{metallayer}$ = volume of metal layer at instant i, m^3

V_{sand_i} = volume of sand through which gas is passing through at instant *i*, m^3

V_{layer_i} = volume of metal layer at instant *i*, m^3

v_1 = velocity of gas at the start (entry point of gas) of vent, m/sec

v_2 = velocity of gas at the end (exit point of gas) of vent, m/sec

t_{cavity} = thickness of the mold cavity, m

t_{mold} = thickness of mold wall, m

H_{mold} = height of the mold, m

H = pouring height of the metal, m

L = total length of the mold cavity, m

W = width of the mold, m

n = no of ingates

w = width of the mold cavity, m

Chapter 1
Introduction

Sand castings are used in order to manufacture complex shapes. The castings are bound to have one or more defect. The presence of defects may subject casting to rejection. The defect causes stress concentration. More time and money would be saved if it ever becomes possible to produce to hundred percent good casting. It may cause casting to fail in fatigue, impact etc. We can minimize defects by taking precautionary measures in the casting processes. This thing can be achieved by predicting these defects prior to metal pouring.

1.1 Blowholes in Sand Casting

There are different types of defects produced in sand casting. A high proportion of casting defects are caused due to evolution of gases. One of the major casting defects caused due to gases is holes (gas holes). Gas holes are pinholes and blowholes. This designation belongs to size of the hole and not its origin. Blowhole is very prevalent cause of casting scrap. Figure 1.1 shows schematic of blowholes, showing blowholes near core, surface blowholes and casting strewn with blowholes.

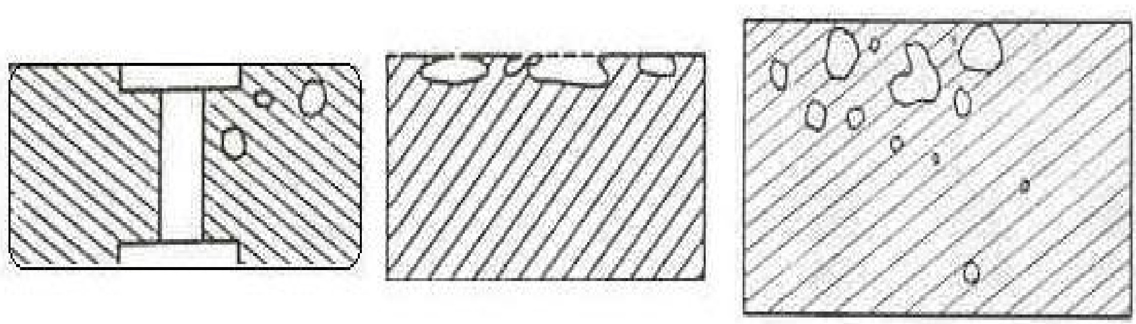


Figure 1.1 Schematic of Blowholes [2]

The blowholes are smooth walled cavities, essentially spherical, often not contacting the external casting surface. The largest cavities are often isolated. In specific cases, the casting surface can be strewn with blowholes. The interior walls of blowholes can be shiny, more or less oxidized or in case of cast iron can be covered with a thin layer of graphite [1]. Figure 1.2 shows some slag blowholes having smooth surface and slag accumulated on smooth surface.

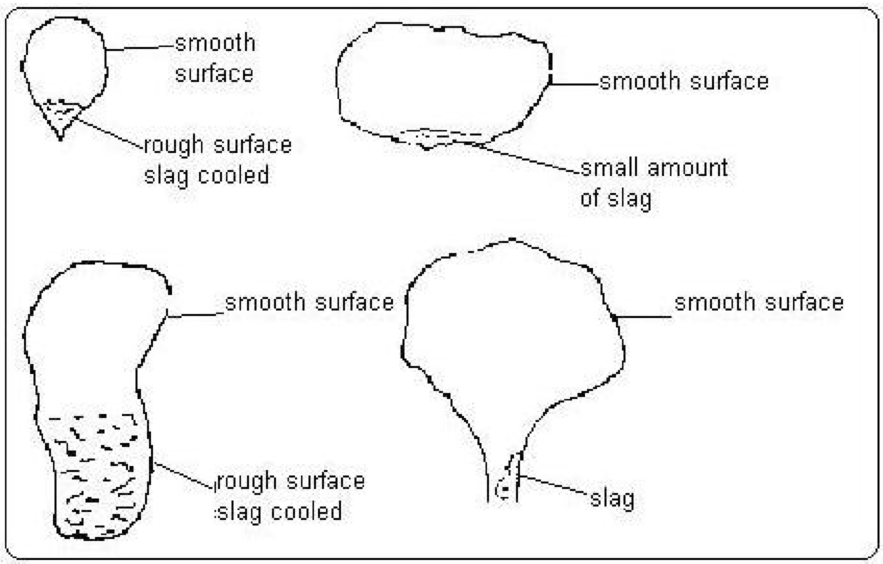


Figure 1.2 Appearance of different Blowholes [3]

The blowholes are usually revealed by machining or by heavy shot blasting. The defect may take the form of well defined bubble shaped cavities beneath the surface of the casting. These forms of holes may arise from entrapment of more than one sort of gas during the course of mold filling and solidification. It is important to know the origin of and reactions producing these gases, so that correct diagnosis and cure can be affected.

Types of Blowholes

When the hot metal is poured inside the sand mold, sand and sand contents gets heated and large amount of gases are produced inside the casting. The main gas producing processes in the mold are [1] [2]:

- Rejection of dissolved gases from the metal
- Entrapment of core and mold gases evolved under pressure
- Reaction of carbon in the metal with oxygen or oxides

The above classification of origin of gases leads to following cases of formation of blowholes [1] [2]:

- Blowholes due to high gas content of the metal

  They are also called as endogenous gas holes or blowholes. These holes are caused due to excessive gas content in the metal bath and rejection of dissolved gases during solidification.

  The gases involved in this defect are hydrogen and nitrogen. Both are soluble in liquid cast iron and relatively insoluble in solid iron. As casting solidifies the insoluble gas is rejected and produces holes between growing crystals. Blowholes from carbon monoxide may increase on size by diffusion of hydrogen or less often nitrogen.

- Blowholes from mold or core gases

  They are also called as exogenous gas holes. These holes are caused due to excessive moisture in molds or cores, core binders which liberate large amount of gas, excessive amount of additives containing hydrocarbons and blacking and washes which tend to liberate too much gas.

  If the gas which is evolved from molds and cores cannot freely escape, it may get trapped in the liquid metal. The bubbles formed remain in the casting during solidification. The gases producing these holes consist mainly of steam, coal gas and hydrocarbon gases from decomposition of organic core binders.

- Carbon oxygen reaction holes

  The gas holes in this group may appear in variety of forms, but the gas responsible is carbon monoxide, produced by the reaction of oxygen containing substances with the carbon present in the cast iron. Manganese sulfide in the oxide rich liquid slag allows the reaction to take place at lower temperatures and facilitates the entrapment of gas in solidifying metal.

- Mechanical entrapment of gas

  They are also called as exogenous gas holes or blowholes. These holes are caused due to insufficient evacuation of air and gas from mold cavity and insufficient mold or core permeability

The blowhole formation is also affected by the parameters like pouring temperature, rate of pouring, slag inclusion, moisture and clay content of mold and sand, type of binder and type of additives used etc.

1.2 Problem Definition

Different commercial software available in casting area are related to mold filling analysis, solidification analysis, design of gating system and defect prediction etc. But yet there is no software developed for blowhole prediction in sand casting.

1.2.1 Motivation

Formation of blowholes in sand casting is a very complex phenomenon. Once the blowhole occurs in casting, if it is not surface blowhole, then it is very difficult to repair it. The foundry rejection due to blowholes may reach up to 30%. Therefore, a system is needed, which will predict formation of blowhole prior to pouring of metal inside mold.

So that proper changes can be made accordingly either in sand contents, metal contents or casting process parameters.

There are many reasons for occurrence of blowhole, therefore it is very difficult to put collectively all the causes. Whatever work is done till now on blowhole, everyone studies a particular cause of blowhole and its remedy. It is necessary to put all things together. There is a lot of work done in casting defect area related to mold filling analysis, solidification analysis and design of gating system, risers etc.

When we consider, blowhole as a defect, very less work has been done for its mathematical modeling. A good number of commercial software are available in market related to mold filling simulation, solidification analysis, gating and mold design etc. They are generally used to visualize mold filling simulation along with prediction of defects like cold shuts and shrinkage cavities, rarely anyone might be having separate software for blowhole prediction. They claim that experienced person can judge occurrence of blowhole from simulation.

Considering all above things, this is an attempt to put all causes and remedies of occurrence of blowholes together. Further, this is an attempt to develop some mathematical model for blowholes, so that one can predict occurrence of blowhole. So that one can easily analyze a particular case of blowhole or can analyze a particular shaped casting before going to cast it, and can check whether blowhole can occur or not.

1.2.2 Objectives

- To identify various causes of occurrence of blowhole and put them together
- To identify corresponding remedies and put them together
- To develop a mathematical model for blowhole.
- To develop a knowledge base related to blowhole.
- To use fluid mechanics techniques for solving mathematical model

1.2.3 Scope and Approach

- In the domain of casting, area of study is limited to sand casting
- Through some industrial visits getting some knowledge about blowhole formation
- Studying various causes and remedies of formation of blowholes
- Studying the origin of gases in mold and methods to reduce generation of these gases
- Studying nature of different types of blowholes
- Developing mathematical model using fluid mechanics techniques
- Developing software for blowhole prediction
- Checking this approach for industrial components having blowhole defect

This is an attempt to develop some systematic approach for blowhole prediction, by developing some mathematical model, using knowledge base available in terms of experience, laboratory data and case studies. Industrial visits were made for getting some practical observations and problem areas related to blowhole formation. This mathematical model is to be checked for some parts with blowhole, collected through industrial visits.

There are different types of blowholes. But, here the focus of the project is on large size blowholes formed during metal casting. These are the major types of blowholes occurring in sand casting and related to basic principle of blowhole formation. They are formed, when pressure of the gases formed inside the mold exceeds the metallostatic pressure.

1.3 Organization of the Report

The report is organized into five chapters. Chapter 2 presents the advanced literature review done in the area of blowhole formation. The chapter includes the principle of blowhole formation, causes of blowholes and remedies of blowholes. Further, the chapter covers different studies related to blowhole formation and approaches suggested in the literature.

The chapter 3 gives a mathematical modeling for blowhole prediction and things needed in order to analyze industrial components. It covers equations derived for gas pressure, temperature and time required for mold filling. The chapter 4 is about the implementation of this methodology, describes the software and then presents the results obtained for different objects. Chapter 5 concludes the report and also presents the future scope of work.

Chapter 2
Literature Review

2.1 Principle of Formation of Blowholes

Blowholes in sand casting result from the physical phenomenon of the pressure of the gas formed inside the mold cavity exceeding the metallostatic pressure of the pouring metal. Mathematically it is represented by the equation [3].

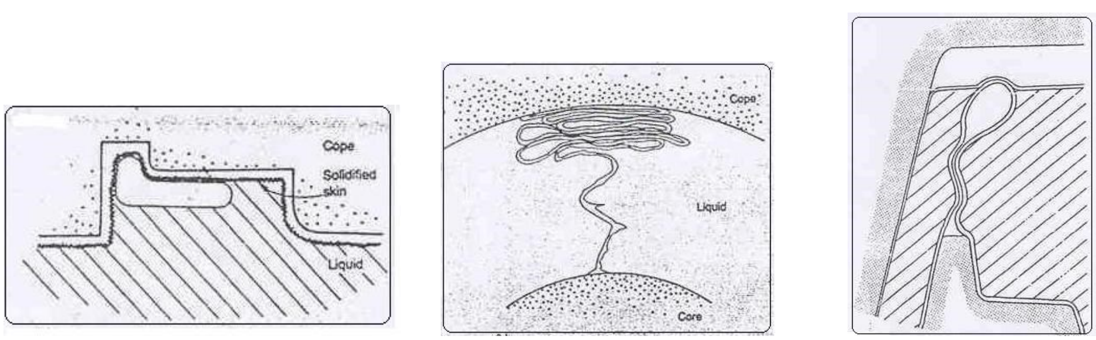
$$P_{gas} > P_{metalostatic} \quad \text{.... (2.1)}$$

Where,

P_{gas} = Pressure of the gas

$P_{metalostatic}$ = metallostatic pressure

When the pressure of the gas exceeds the metallostatic pressure of the metal, a bubble or blow is formed in metal. The bubble of gas appears in the pore of the mold surface. When gas pressure exceeds the limiting value, the bubble elongates and separates from the mold surface. The bubble departing from mold surface is captured by the advancing dendrites, forming blowholes as shown in figure 2.1 [3] [4] [5].



(a) (b) (c)

Figure 2.1 Blowhole Formation; (a) a trapped bubble containing core gases; (b) bubble trail; (c) the detachment of a bubble from the top of the core [5]

Depending on the freezing rate and rate of gas generation, a bubble will actually form in the metal and then be trapped underneath the surface. If the difference between the gas pressure and the metallostatic pressure is equated to surface tension of the liquid metal, we can get the radius (R) of the blowhole formed, as shown in the following equation.

$$P_{gas} - P_{metalostatic} = \frac{2 \times \sigma}{R} \quad \text{... (2.2)}$$

Where,

σ = Surface tension of the liquid metal

R = Radius of the blowhole

The surface tension of ferrous metal varies with the alloy content. A typical value of grey iron is 80 Newton per square meter. Therefore a grey iron casting, 6 inches (0.1524 meter) high a pressure of approximately 11.032 kilo Pascal would be necessary to form a blowhole 1 inch (0.025meter) diameter. However, the prediction of blowhole is not straight forward because conditions at the mold metal interface are not readily described by static equilibrium, the gases are constantly defusing from interfacial region [3].

In addition to high temperature reactions the liquid metal will also absorb hydrogen and nitrogen. In short blowholes are generally the result of complex interaction between the mold-metal and mold-atmosphere and can be accompanied by shrinkage and other complicated conditions [1] [6].

2.2 Causes of Blowholes

There are various causes of blowhole formation, depending on the evolution of different types of gases and various reactions taking place during mold filling phenomenon. Various causes of the blowhole formation are explained in following paragraphs.

2.2.1 Endogenous Blowholes due to High Gas Content of the Metal

The gases involved are hydrogen and nitrogen, which are rejected from solution in the metal during solidification. Both gases are soluble in liquid cast iron and relatively insoluble in solid cast metal. As a casting solidifies, the insoluble gas is rejected and produces (fissure like) hole between growing metal crystals.

2.2.1.1 Hydrogen Blowhole

Most cast iron melted in different furnaces has hydrogen content of 0.8 to 1.8 ppm, provided not exposed to some unusual source of hydrogen. Higher hydrogen content leads to defects depending on size of casting.

In large castings which cool very slowly hydrogen can usually escape by diffusion through outer skin of casting. But in smaller casting the solidification period is too short for hydrogen to diffuse in this way. Such castings produce rounded holes as shown in figure 2.1. The internal surface of these holes is usually clear and bright, that no air penetrated into cavities while the casting was hot. They frequently contain a shiny black film of graphite.

As the hydrogen content of free air is very low, it is obvious that any hydrogen dissolved must come from material containing hydrogen. Most common of these material used is foundry water. Water vapor will decompose to yield hydrogen, on contact with liquid cast iron and produce metal oxides. At the moment of decomposition this hydrogen is in the nascent or atomic form, and is therefore readily soluble in the liquid iron. The amount of hydrogen, which will dissolve will depend upon partial pressure of water vapor in atmosphere in contact with the liquid iron.

The source of water is almost always the damp refractory and ladles for handling the metal. Most of these materials are clay bonded and clay will continue to lose its combined water over a long period, even at a high temperature.

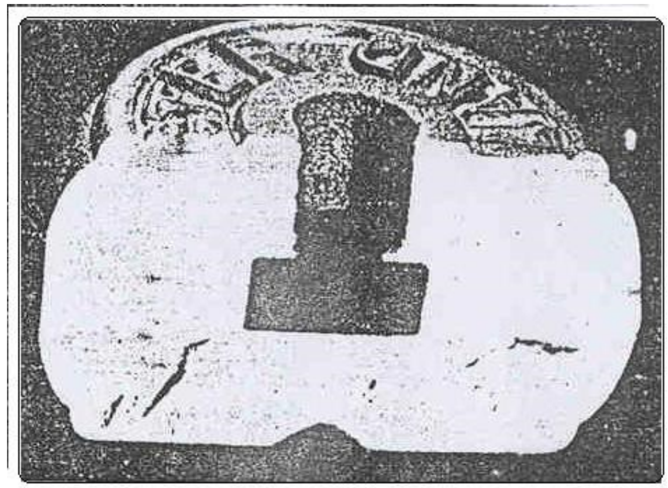


Figure 2.2 Fissure defects due to high hydrogen content [6]

Hydrogen defect can also result from the application of wet patching to a ladle during its use and by wet swabbing and rebuilding of ladle spouts or dips without taking any special care in drying out. The presence of hydrogen is markedly increased by the presence of small amount of Aluminium in Iron. The effect of Aluminium is to increase the rate of reduction of water vapor, thus giving more available hydrogen for solution. Addition of 0.05 percent of Aluminium in an Iron containing no Aluminium produces a severely porous casting compared to sound casting of first. At the highest hydrogen contents the holes become rounded and the metal usually mushrooms out of the top of riser [6].

Removal of Hydrogen

The amount of hydrogen dissolved in melt is governed by the equation 2.3 [i].

$$hydrogen\% = k \times \left(P_{H2}\right)^{1/2} \qquad \dots (2.3)$$

Where,

P_{H2} = It is the partial pressure of hydrogen in the atmosphere over melt

k = constant

Most hydrogen removal techniques are based on equation 2.3 [i] [7].

1. That is reducing partial pressure of hydrogen by bubbling some other dry insoluble gas through the melt. For nonferrous metals, Chlorine, Nitrogen, Helium

or Argon is used. Nitrogen cannot be used for ferrous and Nickel based alloys since it is soluble in these and also forms Nitrides.

2. To pig metal and use later on, much hydrogen diffuse out as they cool and remainder will be removed during remelting.
3. Vacuum melting can be used which prevents the reaction between the solution of gases in metals and combination of reactive elements in the melt.

2.2.1.2 Nitrogen Blowhole

The normal nitrogen content of most grey iron is between 20 and 80 ppm, while malleable iron may contain 100 ppm. When nitrogen contents above this level occur, nitrogen blowhole defects may be produced. Thick sections are more prone to defect, than thin section castings (here they differ from hydrogen). The reason most probably lies in the relatively low rate of diffusion of nitrogen through iron compared with that of hydrogen [6]. Typical blowhole of this type is shown in figure 2.3

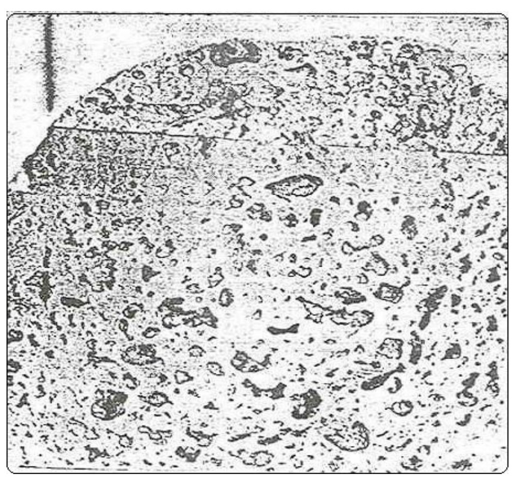


Figure 2.3 Section showing blowholes in casting having nitrogen content [6]

Nature – Nitrogen blowholes are usually in the form of fissures, similar to those caused by hydrogen as shown in figure 2.2, though they have tendency to be more dispersed throughout the casting than hydrogen defect. The interior surface of nitrogen blowholes is usually clean and fairly bright but not as bright as hydrogen defect. Graphite film is observed in defect in smaller holes [6].

Origin – Since atmospheric air contains 80% nitrogen as molecular nitrogen, molten iron is always in contact with a nitrogen rich atmosphere. Molecular nitrogen is only slightly soluble in iron, but atomic or nascent nitrogen is quite soluble [6].

In most grey iron melting units the maximum temperature is barely sufficient to give serious pickup of nitrogen by decomposition of molecular nitrogen from the air. Generally most foundry produce high carbon equivalent value than 3.5% and so never experience trouble with nitrogen gashole defects. Nitrogen content normally does not exceed 100 ppm in such iron. At 140 ppm typical fissure like defect but at 320 ppm large rounded holes in 6 inch (0.1524 meter) diameter casting.

But trend to make very large casting from low carbon equivalent iron, in order to obtain good mechanical properties makes it necessary to find ways of counteracting nitrogen absorption, therefore this is prevented in cupola metal iron. Both the gas hole producing effect and the metallurgical effects of nitrogen could be neutralized by Aluminum and to some extent by titanium. An addition of 0.05% of titanium as titanium swarf made to the ladle or furnace guarantee freedom from defects under condition of high nitrogen content and to represent a safe convenient practical measure to adopt foundries [5] [7].

2.2.1.3 Combined effects of Hydrogen and Nitrogen

There are situations where combined presence of hydrogen and nitrogen produce blowholes. Though nitrogen alone is below levels at which defects would be expected to occur, defect due to combine effect of hydrogen and nitrogen are seen to concentrate into the center of casting. It is extremely unlikely that nitrogen blowholes will be found in cupola metal iron of carbon equivalent value higher than 2.9. It is not easy to differentiate between the blowhole due to hydrogen and nitrogen. But we can easily predict which one of two is a cause of blowhole formation in a particular casting [6].

2.2.1.4 Carbon Oxygen Reaction Blowholes

Under certain condition it is possible for oxygen to react with the carbon present in the liquid cast iron and to liberate carbon monoxide gas. If this gas gets trapped in the solidifying metal a blowhole will result. The most effective source of oxygen is any liquid iron oxide-rich slag, which has become trapped during pouring [6].

The gas producing reaction is:

$$FeO + C \rightarrow Fe + CO$$

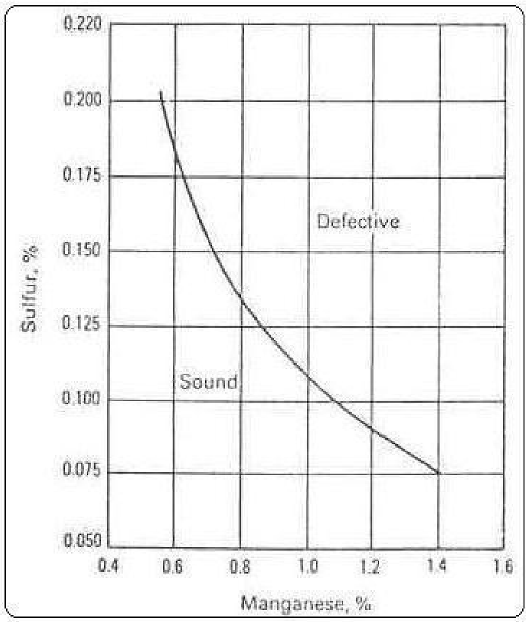
In grey iron, the blowhole defect produced; by the reaction of carbon and oxygen appear in various forms. They may be visible in as cast state or as glossy depression. There are three principle sources of liquid oxide rich slag in iron founding. The cupola slag itself, the slag derived from refractory used for containing and conveying the liquid metal and ladle surface slag produced by chemical action such as oxidation at the liquid metal surface are all source of oxide rich liquid [6].

Also these types of blowhole defects can occur in all types of molds and is aggravated by presence of high water content in the molds. Manganese sulfide inclusions are found clustered in the iron matrix, near the defect and are sometimes present in the slag itself. Cold metal resulting from low pouring temperature is the primary cause of blowholes. Excessive sulfur and manganese levels, however compound the problem. Figure 2.4 shows the sulfur and manganese levels at which sound and defective castings are poured. The higher the sulfur and manganese levels the higher the pouring temperatures must be to avoid blowholes.

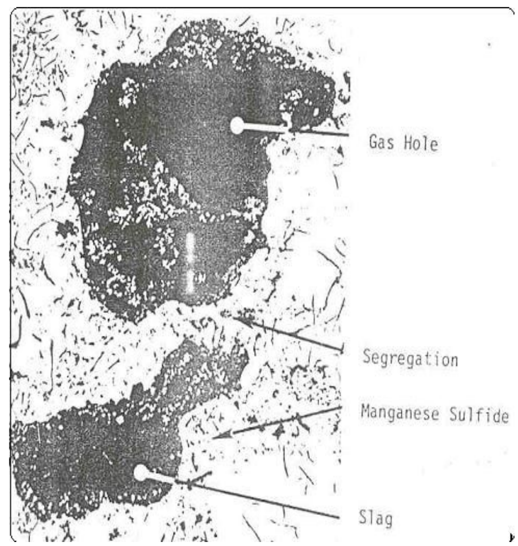
Following sequence of events leads to formation of blowhole. As the temperature of the molten metal falls, manganese sulfide formed and separates from the melt.
The reaction is:

$$Mn + FeS \rightarrow MnS + Fe$$

They float to the surface where they mix with the ladle slag creating the slag of higher fluidity. This slag enters the mold cavity, reacts with the gas precipitating during the eutectic reaction and results in the evolution of CO and the formation of blowholes [8].



(a)



(b)

Figure 2.4 (a) Occurrence of blowhole defects in grey iron castings as a function of sulfur and manganese content, (b) Blowhole defect associated with manganese sulfide segregation [8].

An increase in concentration of either manganese or sulfur will cause manganese sulfide to be precipitated. The reaction proceeds to the right with falling temperature. Thus formation of gas holes involves two factors, first the reaction which could produce a gas and second part played by manganese sulfide. The reaction is essentially, one between fluid oxide rich surface slag and the graphite precipitated during solidification of iron to yield carbon monoxide gas [6] [9].

Only a very fluid slag can be brought into intimate contact with graphite at eutectic temperatures and this low melting point slag is produced by manganese sulfide dissolving in the iron silicate or manganese silicate oxidation slag and lowering its melting point.

Thus the presence of manganese sulfide facilitates the carbon-oxygen reaction, by making the slag sufficiently fluid at the eutectic temperature.

Remedy – If gas holes are to be avoided, while using iron of high sulfur content, high pouring temperatures are necessary. The practice of balancing the sulfur content, by adding more manganese should be changed or will increase the tendency to blowhole formation and manganese in excess of 0.7 percent require correspondingly low sulfur content and high pouring temperatures [6] [10].

The certain cure is to raise pouring temperature, explore the means of reducing sulfur content and adjust manganese level to below 0.7 percent. The metal should be trapped into thoroughly heated pouring ladles and casting ingates should be to avoid stagnant pools of metals during mold filling.

Sometimes it is necessary to remove excess of oxygen present in the steel because carbon oxygen reaction may take place with formation of carbon monoxide bubbles. The usual method is to add an element which has greater affinity for oxygen than carbon. Common elements which are suitable for this purpose are aluminum, manganese, silicon, calcium, zirconium and titanium [6] [9] [10].

2.2.2 Exogenous Blowholes

Another cause of blowhole defect is mechanical entrainment of gaseous elements during pouring. Holes formed from entrained gases are normally large and have rounded shapes. Gas can be entrained by turbulence associated with filling the mold or by high gas pressures formed in the mold during decomposition of mold or core binder [6].

2.2.2.1 Blowholes from Mold and Core Gases

Molds and cores used for iron founding, normally contain binders and additives which liberate gas on heating and if the gas which is evolved during casting cannot escape freely, bubbles will be trapped in the liquid metal filling the mold. The holes caused by these bubbles in the solidifying metal give rise to true blowholes [6].

2.2.2.2 Blowholes from Green Sand Molds

The principal sources of gas from green sand molds are moisture and seacoal, from which it is liberated quite rapidly on heating. The escape of this gas during mold filling takes place via two routes, the pores of the molding sand and special vent holes provided by the Molder.

The holes in the majority of cases are large and have smooth walls. There is optimum moisture content for sand depending upon the proportion of fines and the type of clay used and if this is exceeded then blowholes may be produced. It is up to 4 percent for sands containing fireclay and bentonite. The permeability of the naturally bonded sand is usually low and the effect of moisture is to reduce this even further, at the same time increasing the gas producing potential of the mixture. It is more dangerous than the use of lower permeability base sand at lower moisture content. The addition of seacoal will also reduce the permeability of molding sand and increase the quantity of gas produced. Further, sand having high seacoal content requires more moisture to bring it to a workable condition [6].

A study on behavior of gases in case of a plane wall in dry mold indicates a rapid build up in pressure at the mold metal interface. Rapid pouring promotes high gas pressure within the mold after the latter has filled and under these conditions gas will be forced to escape through the metal. Slow pouring leads to a low pressure after filling the mold, consequently gas which enters the metal before the mold is full aided in escaping by metal movement.

The permeability of the sand should be increased so that gases escape more freely. It can be done by the use of vent tubes, placing the mold on perforated bottom plates and careful placing or stacking of molds to avoid sealing off the gas escape routes. It is also suggested to use exhaust pump for sucking the gas or air from very large molds to avoid blowholes [6] [11] [12].

2.2.2.3 Blowholes Due to Metal Inserts

It is frequently necessary to employ metal inserts in molds for densening the metal or securing cores. These are blowhole producers, in these cases it is important that metal parts which come in contact with liquid iron, are free from moisture, dirt and rust. The blowholes produced by these inserts usually have a definite bubble shape [6].

2.2.2.4 Blowholes from Sand Cores

When cores are heated, gas is evolved and must be removed through the permeability or venting of the core. When venting is inadequate for the evolved gas, blowholes will occur. Typical blowhole from core gas is shown in figure 2.5 [6].

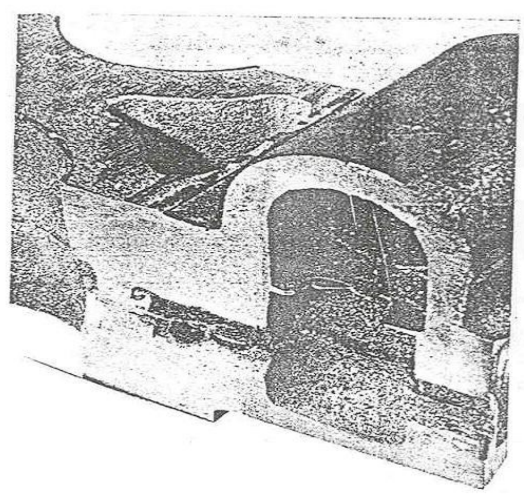


Figure 2.5 Core gas blowholes in cylinder head castings [6]

The rate and quantity of gas evolved from a heated core depends upon the quantity of binders present and their condition. Also, it depends upon the degree of baking. An under baked core has a very high gas evolution rate and should be avoided. On the other hand an over baked core is more liable to break or crack and allow metal to enter and block the vents, blowholes may be formed in either case. The principle gas evolving material is green binder and not the oil. It is observed that slow gas pressure build up should not give blowholes, provided that solidification had taken place before maximum pressure is reached. Thus, rate of evolution and not the total quantity of gas evolved is the important factor [6].

The blowholes may arise due to lower core permeability resulting from the use of very fine sand or from incorporation of very fine material into the mixture. The gas from the cores has to be vented through core prints. Normal core sand with a permeability number of 150 may vent quite satisfactory through a print of 2 inch (0.0508 meter) in diameter, but if same amount of gas has to escape at the same rate through a print half inch (0.0127 meter) in diameter without giving rise to unwanted back pressure then equivalent permeability number would need to be 2400. For this reason most cores require venting. This is usually done by piercing the green core with a wire to produce a hole [6] [12].

2.2.2.5 Water Explosion

As far as casting is concerned dense molds has led to considerable improvement of dimensional accuracy. Water explosion occurs in case of denser molds. In this case there are other forces which press the metal into the sand pores. These forces are caused by explosive evaporation of water during pouring [13].

Spontaneous evaporation of water present in a thin surface layer of the mold, this phenomenon is referred as water explosion. The explosion of superheated water is initiated by metallodynamic shock developed during the casting process. Increase in mold hardness, increases tendency towards water explosion. When a pouring shock can initiate water explosion, we may presume that metal dynamic shock originating from water explosion may in turn initiate new explosions. The shocks caused by water explosion can be very violent [14].

The formation of explosion defects results from the following mechanism demonstrated in figure 2.6. The impact causes a quantity of metal 'A' to penetrate slightly into the passes of mold. Besides it creates a high contact pressure between the metal and the mold surface, resulting in rapid heat transfer from metal to the mold surface.

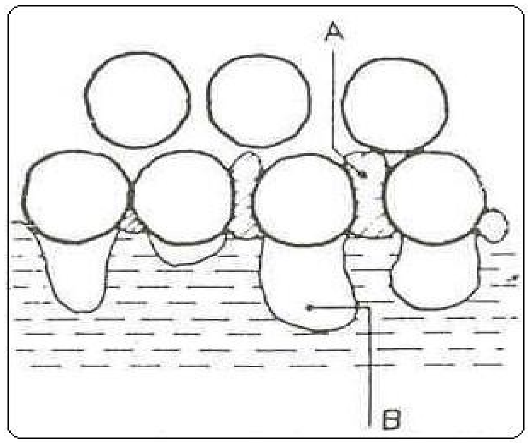


Figure 2.6 Mechanism of explosion penetration shown schematically [13]

This transfer leads to explosive evaporation of water on the mold surface and solidification of penetrated metal tips. The explosive formed steam bubbles 'B' on the sand grains, are forced to enter the liquid suddenly and force it into remaining sand pores. The metal may then penetrate several millimeters into the mold wall. The intensity of explosion determines surface area on which penetration takes place. If the material solidifies rapidly, the steam bubbles may be frozen in. If it stays longer, then steam bubbles can escape through remaining sand pores [13].

Influencing factors are moisture content of sand, permeability of sand, sand temperature, casting wall thickness, casting time, gating technique, clay content and contact pressure between metal and mold wall etc. There are some papers, which give idea about effect of mold hardness on permeability of sand [13] [14].

It is very difficult to predict, the contents of gases formed inside mold. One can just try it by imagining types of reactions happening inside the mold, and hence reaction products.

Some papers from literature available on blowhole gives some case studies, which give idea about different types of gases formed inside the mold, percentage share of them in total gas, for certain casting.

2.3 Related Studies

Researchers have carried out some study related to blowhole formation. The study carried out includes vent and venting design for mold and cores, the relation between gas pressure developed inside the mold cavity and permeability of mold and core sand, effect of venting on the gas pressure developed inside the mold cavity and effect of vacuum on gases and blowholes. These things are explained in detail in following paragraphs.

2.3.1 Gas Pressure and Venting of Cores

Under-venting, especially of cores surrounded by metal is a chronic cause of rejections due to trapped gas. Even if gas is not trapped in the metal, passage of gas through the metal may cause oxide dross, if gas and metal are reactive. Various organic additions to molding and core sands presumably evolve relatively high percentage of non condensing gases on heating. Also, it is assumed for discussion that, organic additions evolve limited amount of water vapor on heating. Williams has presented data on gas pressures generated by organic binders. These data are based on volume of gas generated converted to pressure by standard permeability equation. He used following equation [15]:

$$P_{gas} = \frac{V_{moldesc} \times t_{mold}}{V_{sand} \times f \times \tau} \qquad \text{... (2.4)}$$

Where,

P_{gas} = pressure of gas generated inside mold cavity

V_{gas} = volume of gas generated

t_{mold} = thickness of sand heated

V_{sand} = volume of sand

f = permeability of sand

τ = time

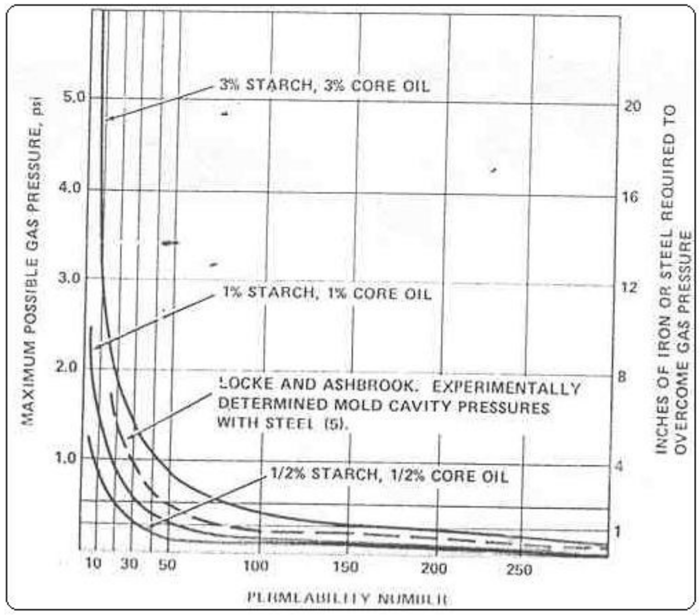


Figure 2.7 Relation between permeability and gas pressure in flat sand-metal interfaces [15]

Figure 2.7 summarizes William's maximum gas pressure for 1%, 2% and 6% organic content composed of half starch, half linseed oil. These are the pressures, those expected in sand surfaces formed by molding sand, that do not extend into the metal and 2.5 inches of sand below sand-metal interface heated to 427 ^{o}C in 12-30 seconds [15]. The gas pressure in a sand configuration extending into the metal can be calculated by multiplying the values of figure 2.7, by surface area of sand in contact with the metals, divided by the area of core print and it is shown in figure 2.8 [15].

The permeability equation (2.4) dictates that, gas pressure vary directly with the distance the gas must pass through a given porous mass. Gas pressures can be reduced to lower values, if vents are properly placed, so that the gas formed in heated faces of the core travels a minimum distance to an unobstructed channel, for passage through core print and out of the mold. This is illustrated in figure 2.8 [15]. There is an appreciable decrease in gas pressure even for 300 permeability core sands. Pressure decreases with venting at an increasingly higher rate as permeability decrease. Figure 2.9 gives idea about, decrease in maximum pressure of gas due to venting. If vents can not be used, gas forming additions should be decreased to the point of core breakage. Grain size of sand should be increased to obtain maximum permeability consistent with surface finish required [15] [16].

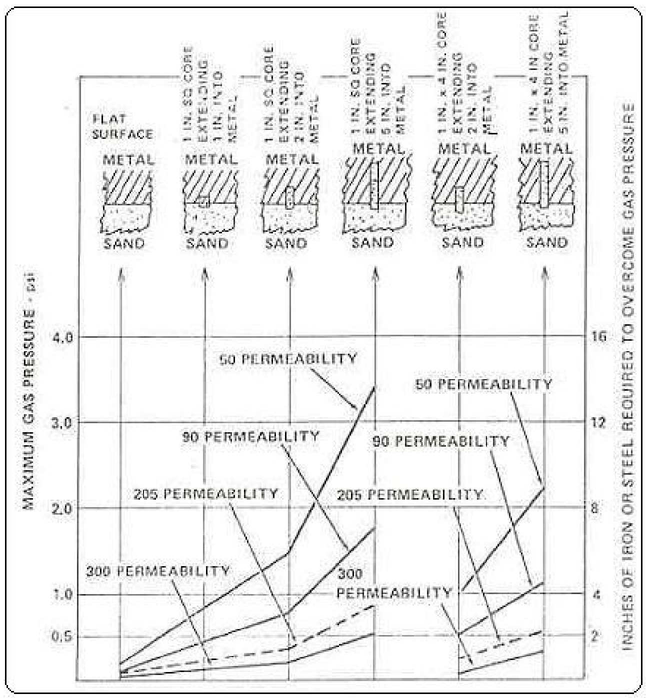


Figure 2.8 Interrelation between core configuration, permeability of sand and gas pressure [15].

Cores of larger section generate less gas. But when larger section cores are vented, consideration should be given to the distance gas must travel from the heated face to nearest vent. Such distances can be quiet large in larger core with only a center vent. Much lower gas pressures can be attained, if such cores are multiple vented with vents. Vents are then tied into center vent, through core print and out through the mold [16] [17].

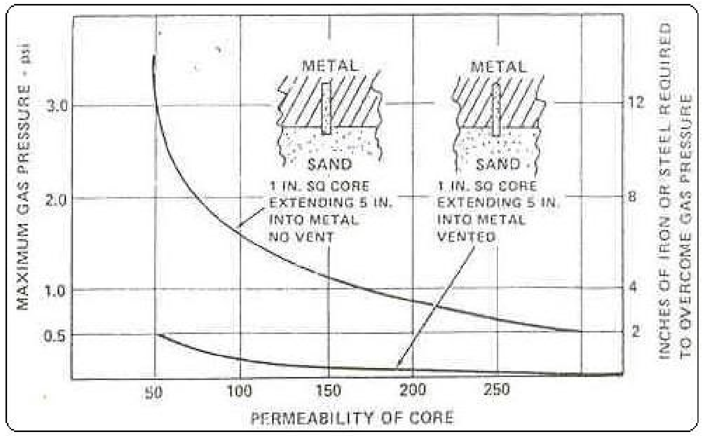


Figure 2.9 Influence of venting on maximum gas pressure [13]

2.3.2 Vent and Venting Design

Vent - is a small hole or passage in a mold or core to facilitate escape of gases when the mold is poured [18].

Venting - is a part of the mold or core forming process that is usually necessary to a variable degree, to produce a quality casting. In some extreme design configurations, it is associated with safe pouring practice. It allows air and gases to escape from the mold [18].

As molds are made with a granular refractory aggregate such as silica sand, the pore spaces produce some natural venting. Unfortunately, to improve casting surface finish with increased compaction, these pore spaces are drastically reduced. This leads to the increase in gas pressure during and after pouring. To prevent gas entrapment, some means of venting becomes necessary [18] [19].

Design of Vent

The diameter of the vent is regulated by, weight of the casting in the sand mold, weight of the core, pouring time required. Standard half inch diameter round stock and tapered vent through the cope should be used for castings weighing more than 12kg [20].

Worman and Nieman present a mathematical procedure to calculate the pressure associated with the core gas evolution for any given configuration [18] [19] [20]. Once the core gas pressure is calculated for a given core material and casting system, one can compare that pressure with metallostatic pressure to ascertain, if the gas will report to the liquid metal or remain within the core.

2.3.3 Improvement of Quality by Vacuum

One of the most efficient methods introduced for prevention of blowholes, is absorption of gases from the mold or core during casting with the help of vacuum pump. In this way, the mold gases are absorbed towards the outside, eliminating the danger of their penetration in the liquid alloy [3] [4].

By imposition of the vacuum in the mold prepared from sand and some bonding material, the following phenomenon is observed.

- Reduction of maximum gas pressure developing at mold-metal interface below zero during metal pouring, until beginning of solidification, thus avoiding the possibility of blowhole formation
- Gas pressure increase with increase in casting temperature. By creating vacuum this gas pressure will decrease and chances of blowhole formation will diminish
- Reduction of gas pressure below zero in cores connected with the system of evacuation directly through the core print, thus avoiding the possibility of generation of gas from the core to penetrate in column of liquid alloy crating blowhole
- Elimination of condensation zone or its shifting away from steel mold interface
- Imposition of vacuum in the sand molds, eliminates vapors avoiding blowhole formation

2.4 Approaches for Blowhole prediction

Two approaches were suggested through literature for predicting blowhole formation and probable remedies. First one is knowledge based expert system, which consists of three stages defect identification, cause determination and remedy suggestion. This approach is experience based and can not be mathematically proved.

Second approach is by mold filling analysis, which consists of mathematical modeling using various physical phenomenons taking place inside the mold. This analysis can be used to find pressure distribution, temperature distribution inside the mold cavity and the time to fill the mold cavity. This approach is difficult to implement as all causes of blowhole formation can not be considered. Further, it is difficult to validate this approach. These approaches are explained in detail in following paragraphs.

2.4.1 Knowledge Based Expert System

Knowledge-based expert system is a branch of Artificial Intelligence in which knowledge provided by a human expert is the basis for the intelligent behavior. It uses computer programs, which use a collection of facts, rules of thumb to suggest solutions to specific problems. Knowledge based expert system use reasoning to solve problems [21] [22].

Foundry related practices are rich in thumb rules and knowledge bases, which can be implemented in such programs to aid foundry men in diagnosis of casting defects like blowholes. Traditionally, diagnosis of blowholes is done in a very experience-based way. These experiences are naturally very important assets to the foundries. However, experiences go with the individual foundry man. It is very desirable to somehow store these experiences electronically. An understanding of these systems does not involve much of conventional computer knowledge [22] [23].

The structure of expert system is as shown in figure 2.10 [21].

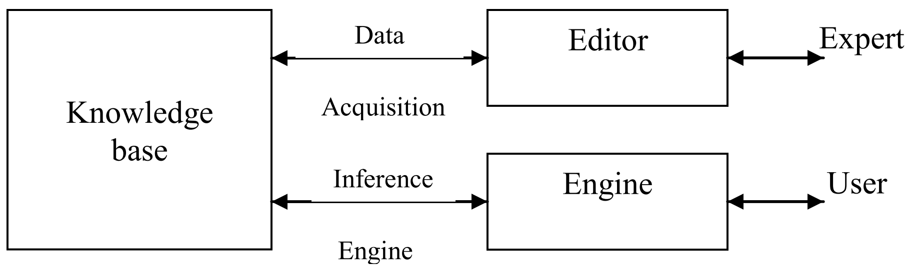


Figure2.10 Structure of Knowledge Based Expert System [21]

The heart of expert system is the set of rules and inference engine. When an expert system is developed from scratch, the bulk of work goes into defining the set of rules to be stored with the program and selecting the strategy for the inference engine to use the knowledge. The inference engine comprises of driving mechanism for the programs and provides the strategy employed to solve problems.

The acquisition module is an interface between the rest of program and the human expert installing the specialized knowledge, which makes the program a specific kind of expert. The knowledge base consists of rules, objects with relevant attributes, relationship between objects and facts. The user interface asks the user for information and displays the program's advice [21].

To develop an expert system for the analysis of blowholes basically involves three steps. The three steps for diagnosing blowholes defect are defect identification, cause determination and remedy suggestion. All these three steps are described one by one in following paragraphs [22] [23].

Defect Identification

In accordance with location, shape, size and distribution of blowholes it is possible to make a preliminary determination of the types of defects (e.g. slag blowholes, surface blowholes, core blowholes etc.). In addition, to provide description of the defects with statements, it is possible to provide illustration to assist users to identify the defects. Once type of blowhole is identified properly, next step is cause determination.

Cause Determination

Because of the need for an immediate solution, in the past, foundry men have tended to select first possible cause that came to mind without examining the other possible causes. This often led to more problems and delays for finding the correct solution. Therefore, it is important to enumerate all possible causes prior to determining the defect cause.

Cause-effect diagram is one approach to enumerate the possible causes. Some of such diagrams are shown in figure 3.1. When all possible causes are known, the operation conditions (e.g. pouring temperature, binder level) are checked, item by item, to determine the potential defect cause.

Remedy Suggestion

After the specific cause has been determined, remedies must be applied to remove the cause and eliminate defect. If particular remedy is not accurate one, and if it does not solve the problem, then again above procedure should be repeated till proper results are obtained.

2.4.2 Mold Filling Analysis

The total time to fill the mold cavity can be determined by integrating the incremental time of filling for all layers from bottom to the top of the mold cavity:

$$\tau_f = \int_0^h \left(\frac{A_i}{\sum_j V_{ingate-j} A_{ingate-j}} \right) dh \qquad \ldots (2.6)$$

The above approach can not predict other phenomenon in mold filling like flow coupling, non linearity and free or moving surfaces. Flow patterns within the mold cavity are important because they provide critical information during filling of casting, influence of the gating system and casting condition on the entrapment of gas and dross, the mold erosion and incomplete filling of molds [24] [25].

A complete model for defect prediction and process optimization during casting consists of two major steps. First, the mathematical equations representing the various physical phenomenon occurring during the casting process are solved simultaneously. These phenomenon include, but are not limited to fluid flow, heat transfer and solidification. Second parts or all of the result of step one, in addition to other data are used as inputs to other defect prediction algorithms, data bases and or knowledge bases to identify the type, location and size of probable defects [26] [27].

Numerical simulation of mold filling is based on fundamental equations for mass momentum and energy balance. These equations, expressed in a differential form are referred to as Navier- Stokes equations.

2.5 Summary of Literature

The blowholes are caused, when pressure of gases evolved during metal pouring exceeds the metallostatic pressure and gets entrapped during solidification of metal. These gases are generated due to various reasons and minimizing their formation can minimize the blowhole formation. These gases can be minimized by controlling moisture content of sand, using low pouring temperatures, low pouring rate of metal and controlling gases soluble in metal, reactions inside the metal and reactions of metal with mold, core, ladle, refractories etc.

The venting of these generated gases is very important. The gas pressure can be reduced to lower values by proper venting of mold and cores. Also, venting can be made effective by proper placement of vent, by using multiple venting of cores, by increasing permeability of sand used. Further, vacuum pump can be used in order to absorb generated gases from mold and core, which reduces maximum pressure inside the mold, elimination of vapors and condensation zone.

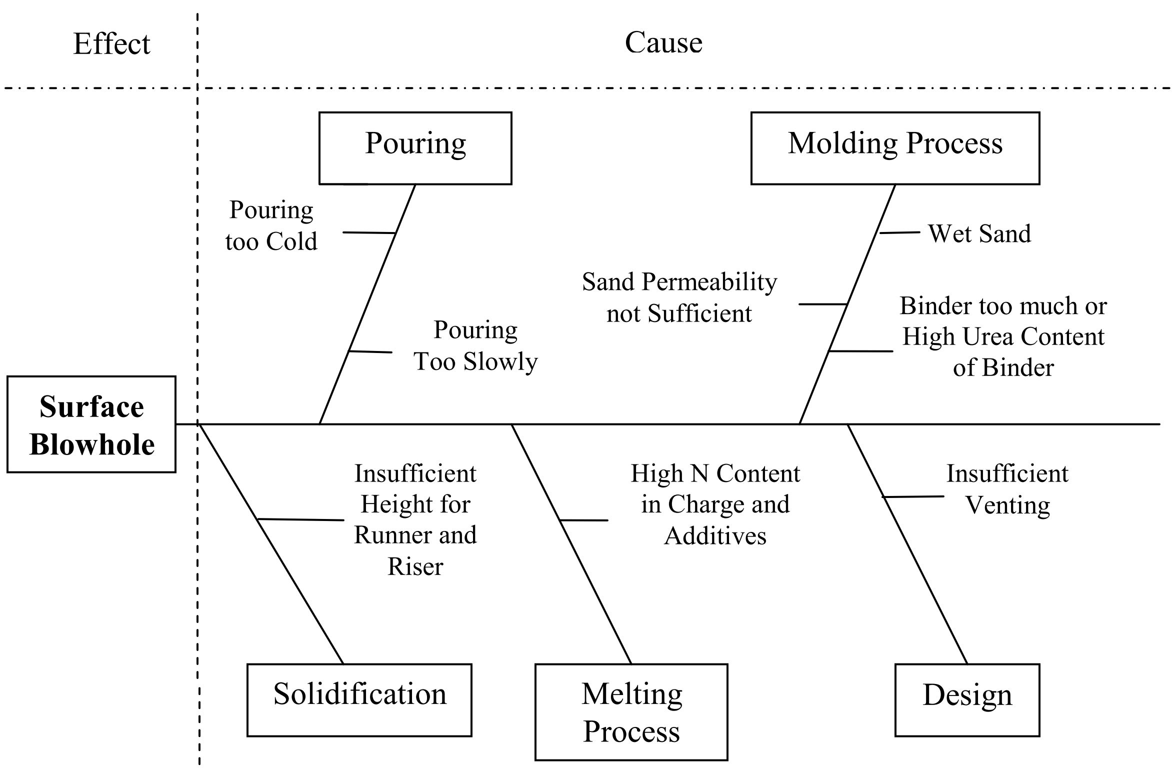
Fluid dynamics techniques can be used to analyze the problem of blowhole formation. Further, the available knowledge in terms of experience, literature can be arranged in order to develop some systematic approach to predict formation of blowholes and its remedies.

The proposed approach for the blowhole prediction is presented in the next chapter.

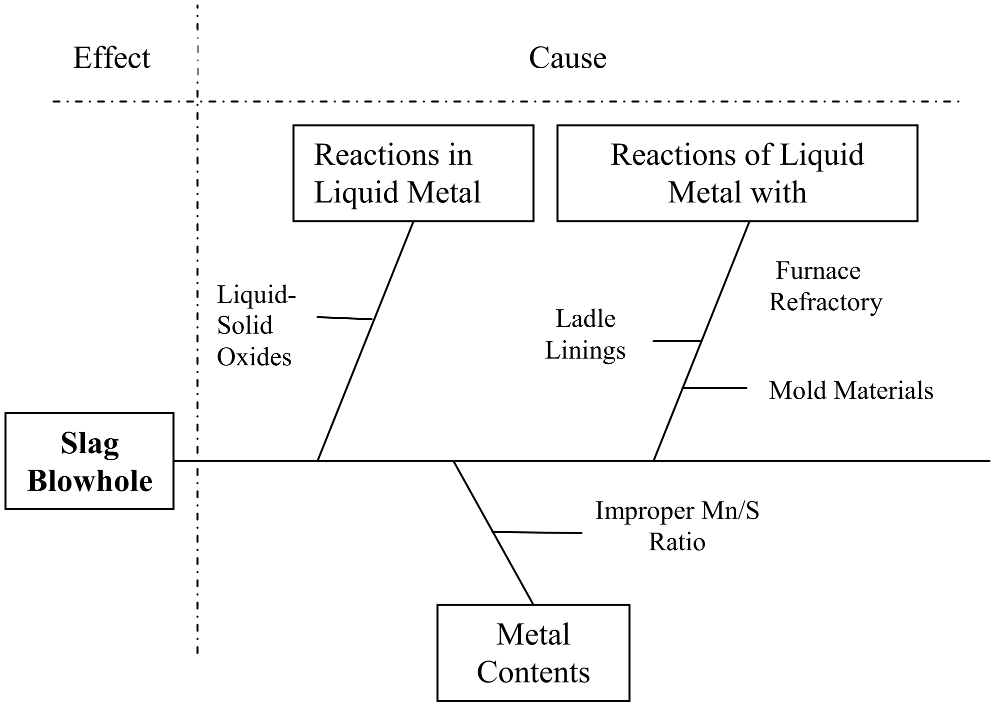
Chapter 3
Modeling of Blowholes

In earlier chapters we have seen, literature review related to blowholes. In order to analyze the particular case properly, it is necessary to prepare some cause effect diagram, and also developing mathematical model, for occurrence of particular type of blowhole. From literature review such cause and effect diagrams were prepared for different types of blowholes, like surface blowholes, slag blowholes, corner blowholes, exogenous blowholes, endogenous blowholes and some of them are shown in section 3.1. Also, by using fundamentals of fluid dynamics, an attempt is made to develop a mathematical model for blowhole prediction in sand casting.

3.1 Cause and Effect Diagram



(a)



(b)

Figure 3.1 Cause Effect Diagrams (a) For surface blowholes, (b) For slag blowholes

3.2 Basic Approach

To analyze these blowholes, we are considering layer by layer filling of the mold cavity by hot metal. If the pressure of the gas inside mold cavity (P_{mold}) is more than the metallostaic pressure ($P_{metallostatic}$) of the liquid metal, then the gas generated inside the mold will enter the liquid metal and result in formation of large size blowholes (of radius 5 to 10 mm). Our focus is on large size blowholes formed in sand casting, due to entrapment of gas in solidifying metal.

There are three types of gating system: top gating, bottom gating and parting line gating. First consider the bottom gating system as shown in figure 3.2. Consider a simple rectangular mold cavity of length *L,* width *w,* thickness t_{cavity} and cross sectional area *A* as shown in figure 3.2 below. We divide this cavity into n number of layers of equal thickness *dl* along length *L*.

When pouring of the metal is started inside mold, initially layer *dl* gets filled at position 1 as shown in figure 3.2. As soon as metal takes position 1, sand in contact with this metal gets heated and gas formation takes place due to heating of sand contents (moisture, binder and additives).

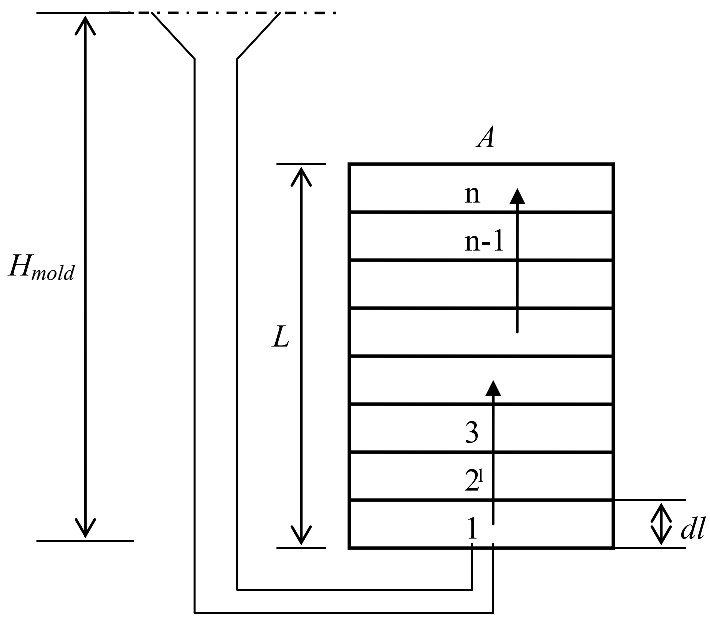


Figure 3.2 Layer by Layer Filling in mold cavity

Further, metal releases some gas during solidification, which is dissolved in hot liquid metal during melting. As pouring continues, the layer *dl* moves to position 2 from position 1 and position 1 is captured by fresh hot metal. Again gas releasing phenomenon takes place due to heating of sand surrounded by hot metal at position 2. This phenomenon continues till the metal reaches to position n.

This gas and air inside mold are under pressure and due to rising metal this pressure increases. When metal moves from position 1 to position n, certain amount of gas-air mixture escapes through sand pores and venting to outside the mold. We calculate gas pressure developed inside mold considering gas generation and escaping phenomenon, while metal is moving up layer by layer. The moment gas pressure exceeds metallostatic pressure; the gas will enter the liquid metal and may result in blowhole formation. Further, we can calculate time required for layer *dl* to move from one position to next position and hence the total filling time.

When we consider heat transfer taking place during process of mold filling, we can calculate temperature drop of metal layer while it is moving from position 1 to position n. This temperature drop is used to calculate the final temperature of layer *dl,* at each position. During solidification of the liquid metal, gases dissolved in the metal during melting are rejected. If the temperature of the liquid metal layer at any position reaches solidus temperature of the metal, then these evolved gases may get entrapped inside solidifying metal and results in formation of pinholes.

Before beginning to derive equations, some assumptions have been made to simplify the problem. Assumptions made are listed below.

- The layer by layer filling of the mold cavity is considered
- The hot metal is poured at constant rate, through pouring basin and height of the pouring basin is the pouring height
- Assume incompressible flow of the liquid metal inside the mold cavity
- All the gases formed during mold filling are ideal gases
- Whole volume of moisture, binder and additives in effective thickness of mold wall gets converted to gaseous state
- Thermal and physical properties of gaseous state of moisture, binder and additives are considered
- Once pouring of hot metal starts, all the gases formed are at pouring temperature
- Properties of air are considered as properties of mixture of gases
- The sand mold is preheated to certain mold temperature
- Conduction heat transfer between two consecutive metal layers is ignored

With these basic assumptions the problem can be solved for simple case. The equations required for layer by layer analysis are derived below.

3.3 Gas pressure developed inside the mold cavity (P_{mold})

Consider a simple mold cavity as shown in figure 3.3; of length 'L', width 'w' and thickness 't_{cavity}'. The bottom gating and total height of mold is shown in figure 3.3

Consider following nomenclature for deriving equations.

ρ = density of the metal

$\dot{m}$ = mass flow rate of the metal

A_i = cross sectional area of mold cavity at instant i

$A_{surface\_i}$ = surface area of mold in contact with metal layer dl at instant i

A_{ingate} = area of ingate

H = pouring height of the metal

H_{mold} = height of the mold

l_i = distance traveled by the metal layer from bottom of the mold at instant i

L = total length of the mold cavity

n = no of ingates

P_{mold_i} = total pressure inside the mold at instant i

P_{air_i} = air pressure at instant i

P_{gas_i} = pressure of evolved gases at instant i

$\Delta P_{permeability}$ = pressure drop of gas due to sand permeability at instant i

$\Delta P_{venting}$ = reduction in gas pressure due to escaping of gases through vents at instant i

ΔP_{escape_i} = total reduction in gas pressure due to escaping of gases at instant i

R = specific gas constant

$R_{moisture}$ = specific gas constant for steam

R_{binder} = specific gas constant for gas due to binder

$R_{additives}$ = specific gas constant for gas due to additives

T_i = temperature of the liquid metal

t_{mold} = thickness of mold wall

$t_{effective}$ = thickness inside mold wall upto which hot molten metal is heating sand contents

V_i = volume of mold cavity at instant i

W = width of the mold

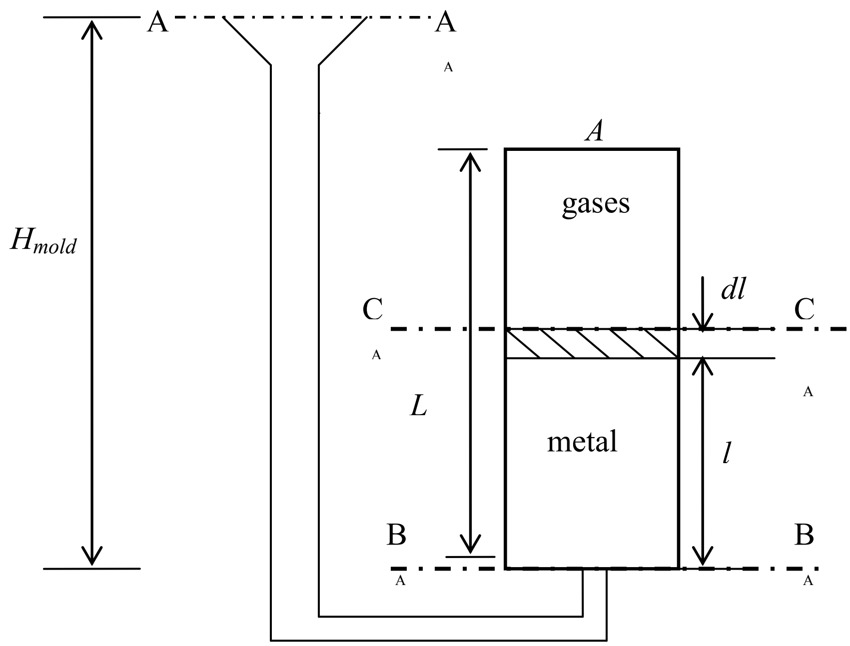


Figure 3.3 A simple mold cavity to be analyzed for gas pressure

Initially inside mold there is only air. After pouring the metal, gases are generated and total pressure above the liquid metal inside mold (P_{mold}) is sum of air pressure and gas pressure. At the same time gases are escaping through mold wall and venting. Therefore, we should reduce pressure of these released gases from mold pressure.

It can be written as

$$P_{mold\_i} = P_{gas\_i} + \Delta P_{air\_i} - \Delta P_{escape\_i} \quad \text{... (3.1)}$$

Where,

P_{gas_i} = pressure of evolved at any instant i (the value of i ranges from 1 to n) which is given by, summation of partial pressures of gases in the mold cavity due to heating of moisture, binder and additives.

$$P_{gas\_i} = P_{moisture\_i} + P_{binder\_i} + P_{additive\_i} + P_{evo\_i} \quad \text{...(3.2)}$$

Where,

$P_{moisture\_i}$ = partial pressure of gas due to heating of moisture at instant i

P_{binder_i} = partial pressure of gas due to heating of binder at instant *i*

$P_{additive\_i}$ = partial pressure of gas due to heating of additives at instant *i*

P_{evo_i}= partial pressure of gas evolved through metal at instant *i*

Each individual pressure can be expressed as,

$$P_i = \left(\frac{m \times R \times T}{V_i}\right) = \left(\frac{m \times R \times T}{(L - l_i) \times A_i}\right)$$

Therefore, we can modify equation 3.2 as below

$$P_{gas\_i} = \left(\frac{m_{moisture} \times R_{moisture} \times T_i}{(L - l_i) \times A_i}\right) + \left(\frac{m_{binder} \times R_{binder} \times T_i}{(L - l_i) \times A_i}\right) + \left(\frac{m_{additive} \times R_{additive} \times T_i}{(L - l_i) \times A_i}\right) \quad \ldots (3.3)$$

In each case mass is given by,

m =1/100 × *(density×percentage of individual quantity in mold sand × surface area on which metal flows × Effective thickness of mold wall upto which molten metal is heating sand contents)*

$= 1/100 \times \rho \times percentage \times A_{surface\_i} \times t_{effective}$

Partial pressure of gas evolved through metal at instant *i*, is summation of partial pressure due to hydrogen and nitrogen escaping during mold filling and they can be calculated using following equations.

$$P_{evo\_i} = P_{evo\_hydrogen} + P_{evo\_nitrogen} \quad \ldots (3.4)$$

$$P_{evo\_hydrogen} = \frac{\rho_{hydrogen} \times V_{hydrogen} \times R_{hydrogen} \times T_p}{V_i} \quad \ldots (3.5)$$

$$P_{evo\_nitrogen} = \frac{\rho_{nitrogen} \times V_{nitrogen} \times R_{nitrogen} \times T_p}{V_i} \quad \ldots (3.6)$$

The amount of hydrogen released by metal, as temperature of metal starts dropping from pouring temperature is 10 ml/Kg of metal. Similarly metal releases 0.02 percent of nitrogen per second during temperature drop of the metal. Accordingly equations 3.7 and 3.8 are written above.

Where,

$$V_{hydrogen} = 10^{-6} \times \rho_{metal} \times V_{metallayer} \qquad \text{… (3.7)}$$

$$V_{nitrogen} = \frac{0.02 \times \rho_{metal} \times V_{metallayer} \times \tau_i}{100} \qquad \text{… (3.8)}$$

Now let us calculate pressure drop due to escape of gases through mold walls and venting. We need to calculate pressure developed due to volume of gases escaping through mold walls and loss of pressure head due to volume of gases escaping through vents.

In order to calculate pressure drop due to gas escaping through mold walls because of sand permeability, we use permeability equation.

$$P_{gas\_perm\_i} = \frac{V_{gas\_i} \times t_{mold}}{V_{sand} \times f \times \tau_i} \qquad \text{… (3.9)}$$

Where,

$P_{gas\_perm\_i}$ = pressure due to generated gases at instant *i*, in N m^{-2}

V_{gas_i} = volume of gas at instant *i*, m^3

t_{mold} = thickness of mold wall, m

V_{sand} = volume of sand through which gas is passing through, m^3

f = permeability of sand, m^{3}N^{-1}s^{-1}

τ_i = time for which gas is passing through mold walls at instant *i*, sec

= time required for layer *dl* to move from current position to next position

Thus, pressure drop due to gases escaping through mold walls is given by,

$$\Delta P_{permeability} = P_{gas\_i} - P_{gas\_perm\_i} \quad \ldots (3.10)$$

In order to calculate the pressure drop due to escape of gases through vents,

Let,

n = number of vents

A_1 = area of vent at entry point of the gas, m^2

v_1 = velocity of gas at entry point to vent, m/s

v_2 = velocity of gas at exit point to vent, m/s

c_d = coefficient of discharge

Volume flow rate through vent = $n \times A_1 \times v_1$

Thus,

$$n \times A_1 \times v_1 = c_d \times A_{mold} \times V_{metal\_i} \quad \ldots (3.11)$$

we get v_1 from above equation and v_2 can be calculated as follows

$$v_2 = c_v \times v_1 \quad \ldots (3.12)$$

$$\text{Loss of head, } H_l = K_1 \frac{v_1^2}{2 \times g} + K_2 \frac{v_2^2}{2 \times g} \quad \ldots (3.13)$$

Where,

K_1 = Loss factor for sudden contraction

K_2 = Loss factor for friction

Pressure drop due to venting is given as,

$$\Delta P_{venting} = H_l \times \rho_{gas} \times g \quad \ldots (3.14)$$

Thus, we can calculate the total pressure drop due to escape of gases through mold walls and through vent by following equation. We use equations 3.14 and 3.10 for this purpose.

$$\Delta P_{escape\_i} = \Delta P_{permeability} + \Delta P_{venting} \quad \ldots (3.15)$$

Now, the metallostatic pressure developed due to pouring of the liquid metal from certain height is given by,

$$P_{metallostatic} = H \times \rho \times g \quad \text{... (3.16)}$$

Using equations 3.1 to 3.7, we calculate the total gas pressure developed inside the mold cavity P_{mold_i}.

Thus, if $$P_{mold\_i} > P_{metallostatic} \quad \text{...(3.17)}$$

Then, blowhole will occur. As pressure due to gases is more than the metallostatic pressure, gas will enter the liquid metal and may get entrapped in solidifying metal. Further, the size of blowhole can be decided by the surface tension of the liquid metal, gas pressure and metallostatic pressure.

We need the time required for the metal layer dl to fill (τ_i) in equations 3.8 and 3.9. In following section, we are deriving equation for τ_i.

3.4 Time required for metal layer to fill

Here, we are analyzing for shape shown in figure 3.4. Here we are assuming incompressible flow of fluid. Also it is assumed that, temperature of metal and temperature of gases formed remains constant during mold filling process.
We use Bernoulli's equation for this purpose.

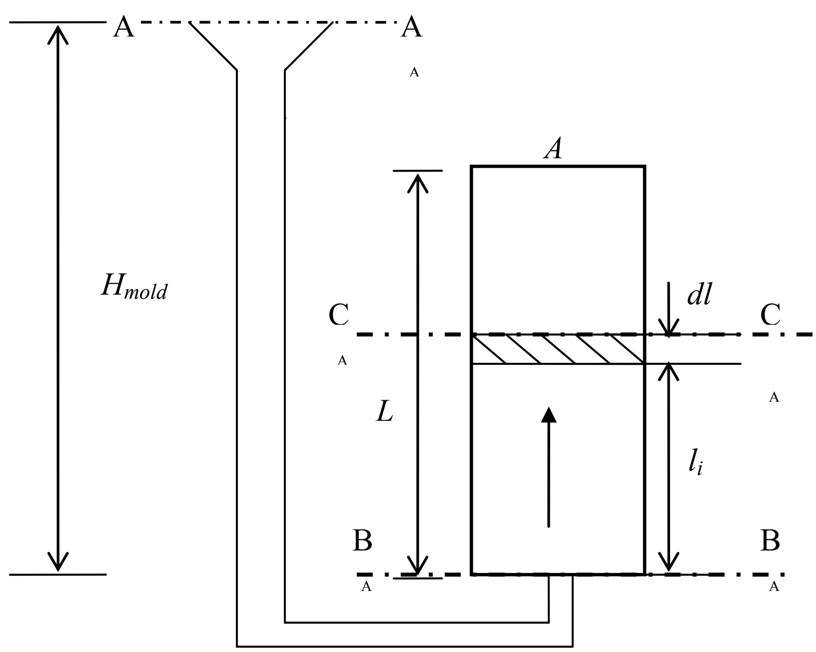
Now, consider the figure 3.4. It is assumed that the pouring height (*H*) of the metal is equal to height of the mold (H_{mold}). Applying Bernoulli's equation, between points A and B, we get the velocity at point B.

$$V_B = C_f \times \sqrt{2 \times g \times (H_{mold})} \quad \text{… (3.18)}$$

C_f = coefficient of friction

.

Figure 3.4 A simple mold cavity to be analyzed for time



Applying continuity equation, between points B and C, we get:

$$n \times A_B \times V_B = A_C \times V_C \qquad \text{... (3.19)}$$

n = no of Ingates

$A_B = A_{ingate}$ = area of ingate

V_B = velocity of metal at ingate

A_C = area at point C

$$V_c = \frac{n \times A_B \times V_B}{A_C} \qquad \text{… (3.20)}$$

Let, V_{layer_i} = volume of metal layer at instant i, m^3

$$\tau_i = \frac{V_{layer\_i}}{V_B} \qquad \text{… (3.21)}$$

We use this time τ_i further in equation for calculating temperature drop.

3.5 Temperature drop

Consider a simple rectangular mold cavity of length *L,* width *w,* thickness t_{cavity} and cross sectional area *A* as shown in figure 3.5 below. We divide this cavity into n number of layers of equal thickness *dl* along length *L.* The metal rises inside the mold cavity from bottom to top (bottom gating). Now suppose we fill the mold with the liquid metal at pouring temperature (T_p).

Consider following nomenclature for deriving equations.

ρ = Density of the metal in Kg/m^3

σ = Stefan Boltzman's constant = 5.67 $\times$ 10^{-8} W m^2 ^{o}K

h = coefficient of convection between metal and surrounding gases W/m^2-^{o}K

h_r = radiation coefficient of convection W/m^2 - ^{o}K

k_{mold} = thermal conductivity of the mold, W m ^{o}K^{-1}

C_m = specific heat of the molten metal kJ/kg-^{o}K

A_i = cross sectional area of the mold cavity at instant *i* in m^2

$A_{surface\_i}$ = surface area of the mold in contact with the metal at instant *i* in m^2

dl = small liquid metal thickness under consideration in m^2

L = length or height of the mold cavity in m

m_i = mass of the liquid metal under consideration at instant *i*, Kg

l_i = distance traveled by metal during pouring at instant *i*, m

T_a = atmospheric temperature, ^{o}K

T_p = pouring temperature of metal in ^{o}K

T_m = melting temperature of metal in ^{o}K

T_{mold} = temperature of the mold ^{o}K

ΔT_i = small change in temperature of layer *dl* at instant *i* in ^{o}K

Consider metal thickness *dl.* Once metal layer *dl* occupies position 1, during the time the layer moves from position 1 to position 2, there will be heat losses by convection and radiation from the top of the melt and by conduction at bottom through the mold wall. When the metal layer occupies position 2 the heat is lost only by convection and radiation from the top of the metal. We are neglecting conduction taking place between the layer at position 1 and layer at position 2 as there will not be much temperature difference between two layers and hence the heat loss will be very less. Thus, the heat loss due to conduction, convection and radiation is written as follows.

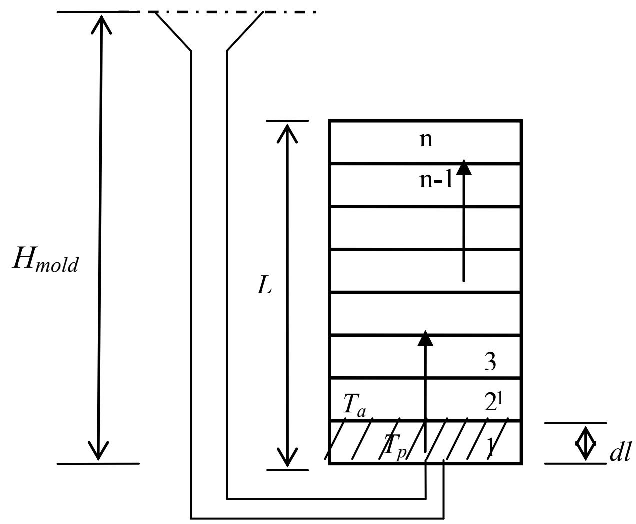


Figure 3.5 A simple mold cavity to be analyzed for temperature drop

Let,

Q_{T1i} = rate of heat lost by conduction through the mold wall at instant *i*

Q_{T2i} = rate of heat lost by convection and radiation from top of the liquid metal layer at instant *i*

$$Q_{T1i} = \frac{k_{mold} \times A_{surface\_i} \times (T_i - T_{mold})}{dl} \quad \text{… (3.22)}$$

$$Q_{T2i} = (h + h_r) \times A_i \times (T_i - T_{mold}) \quad \text{… (3.23)}$$

Heat transfer coefficients are taken at an average temperature of $\left(\frac{T_p + T_m}{2}\right)$

We can write,

$$\left(Q_{T1i} + Q_{T2i}\right) \times \tau_i = m_i \times C_m \times \Delta T_i \quad \text{... (3.24)}$$

$$\Delta T_i = \frac{\left(Q_{T1i} + Q_{T2i}\right) \times \tau_i}{m_i \times C_m} \quad \text{... (3.25)}$$

Where,

C_m = specific heat of the molten metal kJ/kg – ^{o}K

$$m_i = \rho \times dl \times A_i$$

And hr, can be calculated as,

$$h_r = F \times \sigma \times (T_i^2 + T_{mold}^2) \times (T_i + T_{mold}) \quad \ldots (3.26)$$

Where, F is a function of emissivity and geometry of the surface

σ = Stefan Boltzman's constant = 5.67 × 10^{-8} W m^2 K^{-4}

Now temperature of the metal layer *dl,* at position *i* (*i* varies from 1 to *n*) is given by,

$$T_i \; = \; T_{i-1} \; - \; \Delta T_i \quad \ldots (3.27)$$

Thus, at an instant *i*, if $T_i \; \leq \; T_m$

Then, evolving gas from the liquid metal will get entrapped inside the mold and it will result in the formation of small size blowholes (pinholes), as said earlier.

Consider a simple shape as shown in figure 3.6. Details of the component are shown below. It is assumed that the component is cast in sand mold and following parameters for metal, sand, binders and additives are used.

Further, it is assumed that bottom gating is used for mold filling and mold cavity is filled layer by layer. The mold cavity is divided into layer of 5mm thickness along its height and metal layer moves from bottom layer to the top layer. The equations derived earlier are applied and results are obtained for this case.

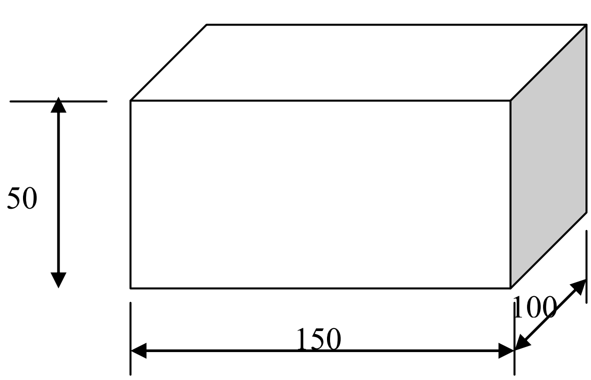


Figure 3.6 Simple rectangular casting

Geometric parameters of mold cavity

Area $=150\times100\times10^{-6}$ m^2,

Length of casting, L = 50mm

Surface area of layer = 2 $\times$ (150+100) $\times dl$

Pouring height, H =150mm

Effective thickness, t_e=2 mm

Geometric parameters of mold

Height = 300×10^{-3} m

Width = 400×10^{-3} m

Length = 450×10^{-3} m

Thickness of mold wall = 50 $\times10^{-3}$ m

Total sand volume = (450 $\times400\times300$) – ($150\times100\times50$)

= 53.25×10^{6} mm^3 = 0.0533 m^3

Thermodynamic properties of mold

k (mold)= 0.5 W/m-K

T (mold) = 353 ^{o}K

Metal properties Aluminium

ρ =2700 kg/m^3

T_p=948 ^{o}K

T_m = 823 ^{o}K

g=9.81m/s^2

Coefficient of convection between metal and gas, h=10 W/m^2-^{o}K

Specific heat of Aluminium, C_m=900 J/ Kg –^{o} K

Binder properties

ρ_b = 1.31kg/m^3

R_b= 12.31 J/kg-K

Percentage=8%

Additives properties

Additive 1

ρ_{ad} = 1.250 kg/m^3

R_{ad}=52 J/kg-K

Percentage =2%

Additive 2

ρ_{ad} = 1.156

R_{ad} =700.0 J/kg-K

Percentage =0.5%

Moisture properties

ρ (at 1 bar and 800 ^{0}C)=0.5 kg/m^3

R= 455 J/kg-K

Percentage=6 %

Sand permeability = 90

Using above parameters, the hand calculation results for the gas pressure (P_{gas}), total gas pressure inside mold (P_{mold}) considering gases escaping through mold walls, time (τ_i) and the temperature of the layer (Ti) as it moves up layer by layer are shown below. The sample calculations along with equations numbers are shown for first layer.

Initially before metal starts entering mold cavity through ingates,
Metallostatic pressure = 3973 N/m^2

For Layer 1,

Metallostatic pressure = 3946.83 N/m^2

l_1 = 5mm

Initially, surface area, $A_{surface\_1}$ = Area+(perimeter$\times$Layerthickness) =0.0175

Volume of Layer = 7.485×10^{-5}

Gas Volume, $V[1] = 0.00068$

Using equation 3.20 and 3.21

$$V_B = 0.7 \times \sqrt{2 \times 9.81 \times 0.15} = 1.19$$

$$\tau_i = \frac{7.485 \times 10^{-5}}{1.19} = 6.23 \times 10^{-5} \sec$$

Using equation 3.2 and 3.3

$$P_{mold\_i} = P_{gas\_i} + \Delta P_{air\_i} - \Delta P_{escape\_i}$$

$$P_{gas\_i} = \left(\frac{m_{moisture} \times R_{moisture} \times T_i}{(L - l_i) \times A_i} \right) + \left(\frac{m_{binder} \times R_{binder} \times T_i}{(L - l_i) \times A_i} \right) + \left(\frac{m_{additive} \times R_{additive} \times T_i}{(L - l_i) \times A_i} \right)$$

$P_m = 0.5 \times 0.0175 \times 0.002 \times 0.06 \times 455 \times 948/0.00068 = 666$

$P_b = 1.31 \times 0.0175 \times 0.002 \times 0.08 \times 12.31 \times 948/0.00068 = 62$

$P_{ad1} = 1.25 \times 0.0175 \times 0.002 \times 0.02 \times 52 \times 948/0.00068 = 64$

$P_{ad2} = 1.16 \times 0.0175 \times 0.002 \times 0.005 \times 700 \times 948/0.00068 = 199$

$P_{gas} = 997$ N/m^2

Now, Increase in air pressure,

$$m_{air}[1] = \frac{P_{air}[0] \times V[0]}{R_{air} \times T_{air}}$$

$$= \frac{1.01321 \times 10^5 \times 0.0008}{287 \times 948}$$

$$P_{air}[1] = \frac{m_{air} \times R_{air} \times T_{air}}{V[1]} = \frac{m_{air} \times 287 \times 948}{0.00068} = 117647 \text{ N/m}^2$$

Using Equations 3.9 and 3.10 we get pressure drop due to permeability,

$$P_{gas\_perm\_i} = \frac{V_{gas\_i} \times t_{mold}}{V_{sand} \times f \times \tau_i} = \frac{0.0068 \times 50 \times 10^{-3}}{0.0533 \times 90 \times 4.4 \times 10^{-5}}$$

$$(\Delta P)_{permeability} = 995$$

Using Equations 3.11 to 3.14 we get pressure drop due to venting,

$$\left(\Delta P\right)_{venting} = H_l \times \rho_{gas} \times g$$

Loss of head, $H_l = 0.375 \times \frac{v_1^2}{2\times g} + 2 \times \frac{v_2^2}{2\times g}$

$$A_{ingate} = A_{sprue}$$

$$A_{mold} \times V_{metal\_i} = A_{ingate} \times V_{ingate}$$

$$150 \times 100 \times 10^{-6} \times V_{metal\_i} = 50 \times 10^{-6} \times V_B$$

$$150 \times 100 \times 10^{-6} \times V_{metal\_i} = 50 \times 10^{-6} \times 1.19$$

$$V_{metal\_i} = 3.97 \times 10^{-3}$$

$$n \times A_1 \times v_1 = c_d \times A_{mold} \times V_{metal\_i}$$

$$3 \times 78.54 \times 10^{-6} \times v_1 = 0.7 \times 100 \times 150 \times 10^{-6} \times 3.97 \times 10^{-3}$$

$$v_2 = 0.95 \times v_1$$

$$H_l = 3.48 \times 10^{-3}$$

$$\left(\Delta P\right)_{venting} = 0.1044$$

P_{mold} = Totalgaspressure[i]= $P_{air}[1]$ - $P_{air}[0] + P_{gas}[1]$ - Pre*suredrop*

= 16652 N/m^2

Now, Let us calculate the temperature drop

Using equation 3.26,

$$h_r = \varepsilon \times \sigma \times (T_i^2 + T_{mold}^2) \times (T_i + T_{mold})$$

$$h_r = 0.4 \times 5.67 \times 10^{-8} \times (948^2 + 353^2) \times (948 + 353) = 30$$

Using equation 3.22, 3.23 and 3.24 as below,

$$Q_{T1i} = \frac{k_{mold} \times A_{surface\_i} \times (T_i - T_{mold})}{dl}$$

$$Q_{T11} = \frac{0.5 \times 0.0175 \times (948 - 353)}{0.005} = 14.88$$

$$Q_{T2i} = (h + h_r) \times A_i \times (T_i - T_{mold})$$

$$Q_{T21} = (10+30)\times A_i \times (948-353) = 357$$

$$\left(Q_{T1i} + Q_{T2i}\right)\times \tau_i = m_i \times C_m \times \Delta T_i$$

$$\left(14.88+357\right)\times 6.23\times 10^{-5} = 2700\times 0.075\times 10^{-3}\times 900\times \Delta T_1$$

$$\Delta T_1 = 0.0001$$

for first layer there is temperature drop from bottom of cavity also,

It comes out,

$$\Delta T_{bottom} = 0.0001$$

$$T_i = T_i - \Delta T_i$$

$$T_1 = T_0 - (\Delta T_1 + \Delta T_{bottom})$$

$$T_1 = 948\ ^{o}K$$

Summary of results obtained for first layer is as below,

Metallostatic pressure = 3946.83 N/m^2

Ingate velocity, V_B = 1.19 m/s

τ_i = 6.23×10^{-5} sec

P_m = 670.973 N/m^2

P_b= 63.415 N/m^2

P_{ad1}= 63.9022 N/m^2

P_{ad2}= 162 N/m^2

P_{gas}= 198.883 N/m^2

P_{air} =117647 N/m^2

$\left(\Delta P\right)_{permeability}$ = 995

$\left(\Delta P\right)_{venting}$ = 0.10

P_{mold}= 16652 N/m^2

h_r =30 W/m^2-^{o}K

Q_{T1} = 15

Q_{T2}= 357

ΔT_1 = 0

T_2 = 948 ^{o}K

3.6 Requirements for 3-D Simulation

To analyze the particular component (object) for blowhole prediction, we need a CAD model of the component. We need to slice (passing the slicing planes) this component along its height in order to get number of layers along the height of the component.

Further, we need area (cross sectional area), surface area and volume of the layer at each of these slicing planes. We pass all this geometrical data as input to the all above equations derived earlier in this report and we get the results of pressure, temperature and time at each layer.

For this we need a certain file format that can be read by a computer program. We select STL format of geometrical model of the component. We need to write a program to read this STL format and then area, perimeter and surface area of the component. Detailed description of STL format is given in next section.

The overall methodology to be followed for finding area, surface area and volume of the component (CAD model) is divided into following phases

- A model or component is modeled on CAD system. The model must be represented as closed surfaces to define an enclosed volume.
- The solid model to be built is next converted into a format called ".STL" (STereoLithography). The STL file format approximates the surfaces of the model by triangulated facets.
- Reading STL file and store the data in proper data structures.
- Slicing STL file and storage of points. Pass the slicing planes along the height of the component and store the points obtained in data structure.
- Using points stored, finding area (cross sectional area), perimeter and surface area of the STL file (component).
- Using above geometrical data for calculating pressure, time and temperature from equations derived earlier in this chapter.

3.6.1 STL format

The term STL stands for stereo-lithography tessellation language which has now become the de facto data exchange standard in CAD/CAM applications. In this format the object is represented as a collection of triangular facets, each facet described by three vertices and a normal pointing outwards from the facet. Generally, the biggest advantage of STL format is its simplicity of representation. It is one of the simple and fast developing file format used for product data exchange between various systems particularly in Reverse Engineering and Rapid Prototyping systems. A detailed explanation of STL format is given in following paragraph.

The term STL, refers to the representation of 3D forms as boundary representation solid model constructed entirely of triangular facets. The STL format states that the facets are described by the X-Y-Z coordinates of their three vertices defined in a specific way and a surface normal vector that indicates the orientation of the facet and which side of it faces out. The simplest among planar entities, the triangle is used to describe everything.

Here is an example of a typical ASCII format STL file:

…………………………………………………………………………………………

```
Solid model
    Facet normal 0 1 0
        Outer loop
            Vertex 1 0 0
            Vertex 1 0 1
            Vertex 0 0 1
        End loop
    End facet
End solid
.
```

…………………………………………………………………………………………

Figure 3.7 Sample STL file

3.6.2 File reading and data structure formation

As seen in the previous discussions, STL format has become a *de facto* standard for data exchange between CAD/CAM applications like reverse engineering and rapid prototyping. So the input for project will be taken in STL format i.e. STL files of the object. These files are read to get the basic facet data i.e. vertices and normal of each facet. This entire data is packed into one data structure representing the component data as given in table 3.1.

Table 3.1 Data structure for component data

Component	Data
Object	No of vertices No of facets No of edges Pointer to vertex list Pointer to facet list Pointer to edge list

Using a simple algorithm the data can be read from the files and stored in a data structure which is of the format as given below

Table 3.2 Data structure for data storage

Facet No	Vertices	Normal
N	V1 (x1,y1,z1) V2 (x2,y2,z2) V3 (x3,y3,z3)	(n_x,n_y,n_z)

3.6.3 Slicing STL file

Slicing STL file means slicing triangles. The triangle in a STL file is shown below in figure 3.8**.** Three vertex of triangle are numbered as P_0, P_1 and P_2 as shown. When a slicing plane is passed through STL file along z axis, first it checks the number of triangles to be sliced by plane. The test condition for this is at least one vertex of triangle should be above or below the plane as shown in figure3.8.

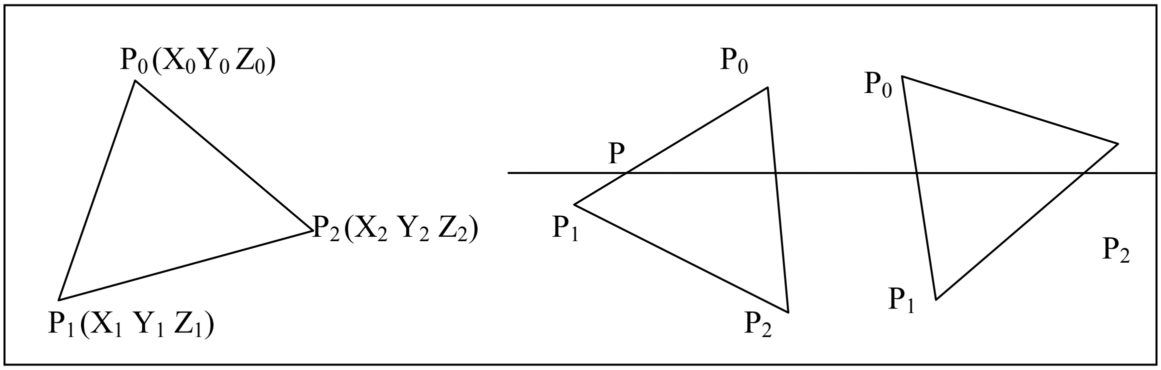


Figure 3.8 Slicing STL file

The coordinates of point of intersection P (X Y Z) of line joining vertex P_0 and P_1, are obtained as follows.

We have,

$$P = P_0 + u(P_1 - P_0) \qquad \text{... (3.28)}$$

Thus, we can write,

$$X = X_0 + u(X_1 - X_0) \qquad \text{... (3.29)}$$

$$Y = Y_0 + u(Y_1 - Y_0) \qquad \text{... (3.30)}$$

$$Z = Z_0 + u(Z_1 - Z_0) \qquad \text{... (3.31)}$$

As we are slicing along z plane, u is given by,

$$u = \frac{(Z - Z_0)}{(Z_1 - Z_0)} \qquad \text{... (3.32)}$$

Then using equations 3.29 and 3.30 we can find out X and Y coordinates of the point.

3.6.4 Area, Perimeter and Surface area Calculation

Once the STL file is sliced at certain height, the points obtained are stored. The perimeter is calculated by calculating the distance between two consecutive points and adding all these distances. Surface area is equal to perimeter into layer thickness.

Area is calculated using trapezoidal rule as shown below.

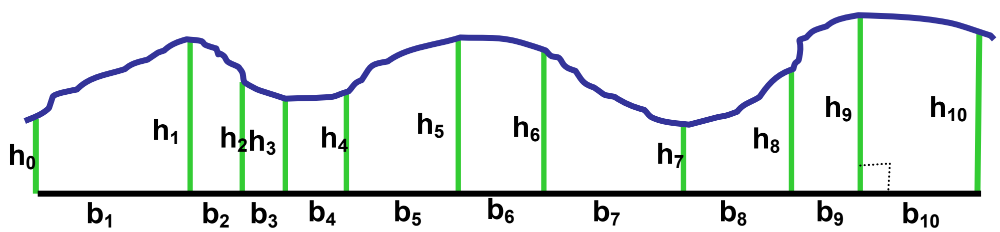


Figure 3.9 Area Calculation Using Trapezoidal Rule

Area of Trapezoid = ½ $b_1(h_0+ h_1)$

Total Area = ½[b_1 $(h_0+ h_1)$ + b2$(h_1+ h_2)$ + $b_3(h_2+ h_3)$ + $b_4(h_3+ h_4)$ …… + $b_{10}(h_9+ h_{10})$]

For equal intervals b (i.e. $b_n=b_{n+1}$):

Total Area = $b[h_0/2 + h_1 + h_2 + h_3 + h_4 + h_5 + h_6 + h_7 + h_8 + h_9 + h_{10}/2]$

Chapter 4
Implementation and Case study

4.1 Overview of Software Developed

The software developed for prediction of blowholes in sand casting has been named as "Blow Detect". It is being developed on Visual C++ Version 6.0, using OpenGL. OpenGL is a programming interface for producing interactive 3-D applications on a wide variety of platforms.

The software imports STL files of object (solid model) under study for blowhole prediction and analyses the object according to the instructions and specifications of the user. During the process user can view status of the process after each phase.

4.1.1 User Interface

The menu structure of "Blow Detect" is shown in the figure 4.1.

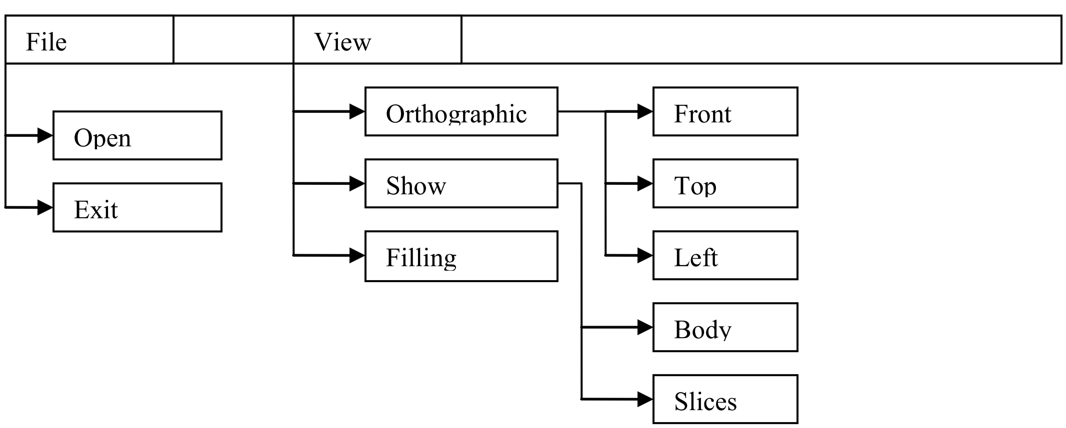


Figure 4.1 User Interface 0f the Software

The “File” menu contains two sub menus ‘open’ to import the STL files and ‘Exit’ to close the program. “View” menu contains the sub menus orthographic, show and fill. “Orthographic” submenu gives options to view the models in front, top & side views. “Show” submenu gives options of displaying body and slices (slicing planes along height of the object). “Slice” sub submenu orders the program to slice the body along the given axis, calculating area, perimeter, surface area and volume at all slicing planes and displays these slicing planes in red color. “Filling” submenu gives option to display filling the mold cavity with the metal, at the same time calculates pressure, time and temperature at each of these slicing planes.

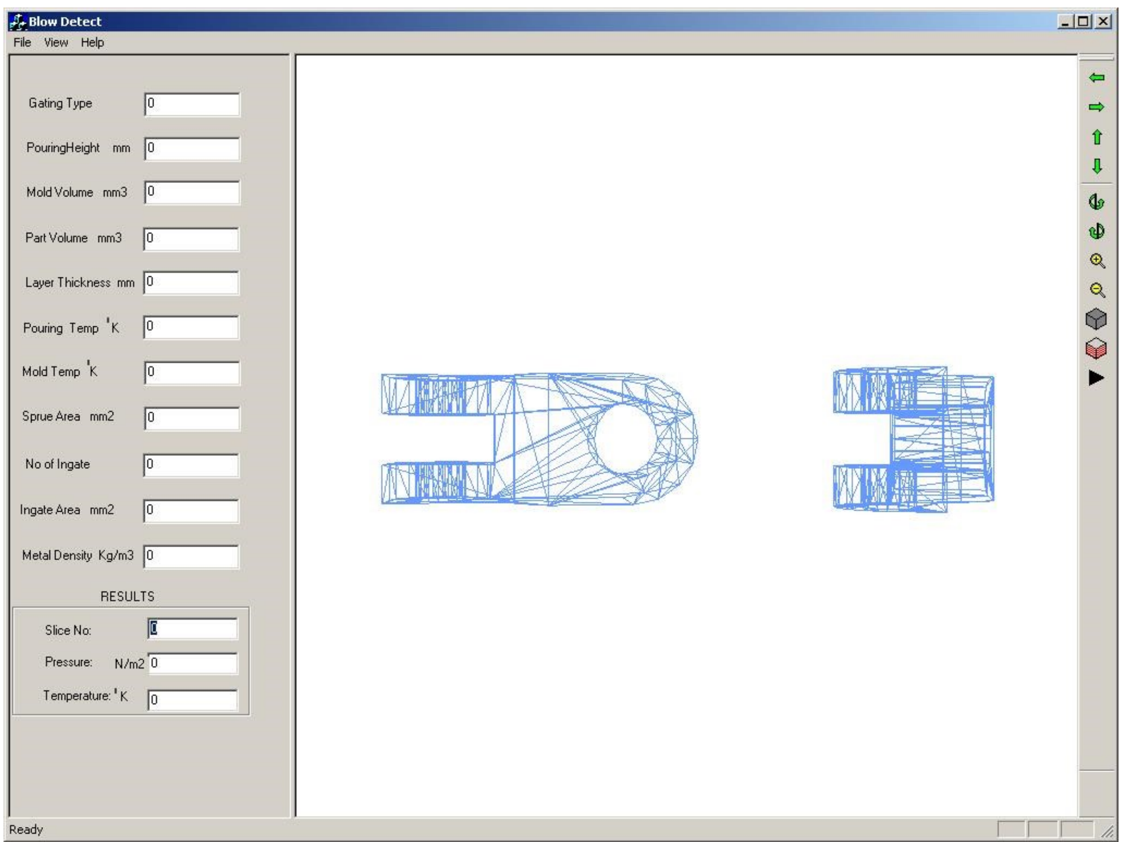


Figure 4.2 Screen Structure of the Software

Apart from the main menu a tool bar to right hand side of the screen and a dialog box to left hand side of the screen is provided as shown in the figure 4.2. Button toolbar contains buttons to change the view, pan, zoom, rotate, slice and fill. Rotate option is provided to test the aligning capability of the software. User can rotate the object about its center about any axis in the space. Using translate option user can translate the object in the space. The slice button is shortcut to the “Slice” option in “View” menu. Similarly a shortcut button is provided to start and to pause the filling of the mold cavity.

The dialog box is provided to the left of the screen, so that user can enter the values as input to the program for calculating pressure, temperature and time during mold filling. The dialog contains gating type (enter 1 for bottom gating, 2 for parting line gating and 3 for top gating), mold volume, part volume, layer thickness, pouring height, pouring temperature, mold temperature, sprue area, ingate area, number of ingates and metal density. If nothing is entered in dialog box the program will take default values.

At the bottom of dialog box results of software are shown. Result dialog box shows the slice number, pressure and temperature at this slice number. At any instant during mold filling user can pause the mold filling using pause button in toolbar, and can see the values of pressure and temperature in result dialog box.

4.1.2 Basic Procedure and Output of Software

The basic procedure for analyzing the object for possibility of blowhole and pinhole occurrence can be described as follows

- A model or component is to be modeled on CAD system. The model must be represented as closed surfaces to define an enclosed volume.
- The solid model to be built is next converted into a format called “.STL” (STereoLithography). The STL file format approximates the surfaces of the model by triangulated facets.
- User should open this STL file in the software through file menu. Further, user should slice the file in order to display slicing planes and calculating geometry related data.
- User can enter relevant values in the provided dialog box

- User should fill the object in order to get pressure, temperature at all slicing planes.
- The mold cavity (STL object file) gets filled with red color. If at certain layer or slicing plane, gas pressure inside the mold cavity exceeds the metallostatic pressure then filling color changes to green color.
- The results of pressure, time and temperature at each slicing plane are shown in the result dialog box.
- The screen of the software shows front and side view of the object. Further, it shows some inputs like pouring height, metal used, pouring temperature etc. given by user to the software

The flowchart of the software is shown in the next section 4.2 on next page.

4.2 Flowchart

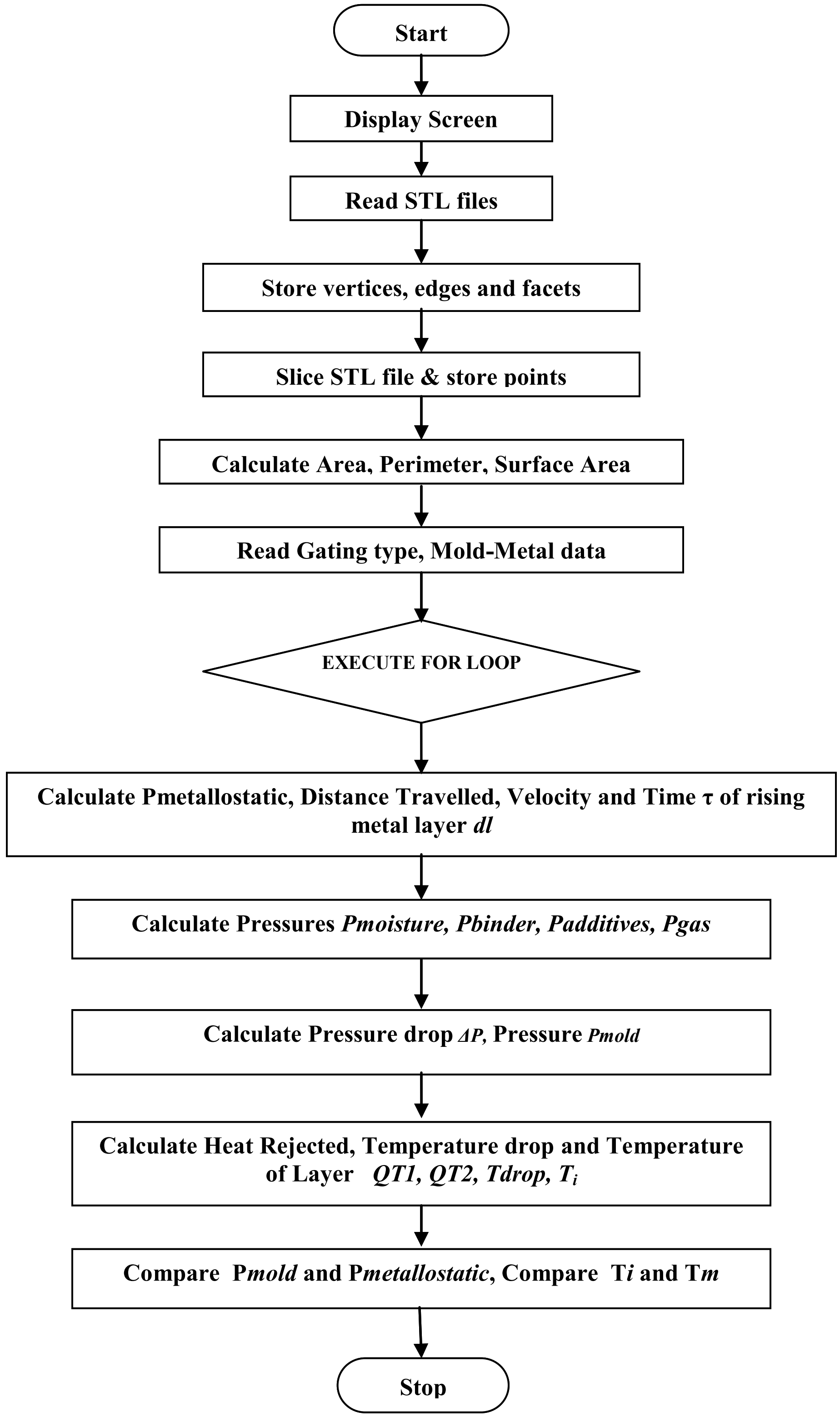


Figure 4.3 Flowchart

4.3 Industrial case study – Results of the software

In earlier chapters, we have seen different causes of blowhole formation, their remedies. Also, we saw the mathematical approach required for analysis of blowholes. By keeping these things in mind, we strongly found the necessity of industrial visits, and accordingly visits to following companies were arranged.

4.3.1 Observations through Industrial Visits

1. Birla Peruchini Aurangabad

This company uses *resin coated sand* for casting purpose and also furnace used is electric furnace. Further except metal pouring all other processes are automated, therefore there are no blowholes. But still they suffer from pinholes, which can be said as a form of blowhole, and they are caused due to slag formation in metal. Observations made in this company are not mentioned in report.

2. Aurangabad Foundries Pvt. Ltd

A visit was made to Aurangabad Foundries Ltd, Aurangabad. The photograph of the component is shown in the figure 4.4 and figure 4.5 below. Following details related to process, metal and mold are noted during the visit.

Observations

- Green Sand Mold
    - 80% old sand
    - 20% new sand
    - Permeability – 90 to 100
    - Graphite powder sprinkled on mold internal surfaces (for good surface finish)
    - Talcum powder sprinkled on pouring basin for smooth metal flow

Figure 4.4 Photograph of Bush *Figure 4.5 Photograph of Pulley*

- Sand Additions
  - Bentonite 4%
  - Dextrine 4%
  - Coal Bond 0.5%
  - Moisture 6%
- Metal Used
  - Pig iron
  - Pouring temperature 1500^{o}C
  - Metal is held for 1min, before pouring (to lower temperature and reduce gas formation)
- Ladle Additions
  - This is done to get composition according to standards
  - Si 0.5%
  - Mn 0.6 to 0.8%
  - Ladles are well dried before pouring
- Gating System
  - Downsprue Φ 10-12mm
  - 2 Ingates 10x10 mm (triangular section)
  - Parting plane height 4inches

- Core is present (Φ = 42mm)
    - Core print Φ= 42mm, 35mm on both sides
    - Core sand addition
- Other Observations
    - Moisture is not getting added, during the process by any other means
    - The casting in which blowhole occurred, poured after 45minutes of starting of metal pouring from furnace
    - Cupola furnace is used
    - The metal slag is removed from furnace and also from upper metal surface before pouring
- Some slag separator was added in ladle
- According to foundry man – The blowhole in above figure, occurred as he has not provided any *means for gas escaping* from other end, as gating is located to one end.

The solid models for components, bush and pulley are drawn in solid modeling package. STL files of these components are made from these solid models. These STL files are simulated in the program. The following parameters are used as a input to the program. Thermodynamic and physical properties for binder, additives and moisture are for gaseous state.

Geometric parameters of mold

Mold Volume (for bush) = $300 \times 400 \times 450$ mm^3

Mold Volume (for pulley) = $300 \times 450 \times 450$ mm^3

Pouring Height (for horizontal bush) = 142.5 mm

Pouring Height (for vertical bush) = 255 mm

Pouring Height (for pulley) = 128 mm

Thickness of mold wall = 50mm

Total sand volume = Mold volume- Volume of mold cavity

Layer thickness = 1mm

Thermodynamic properties of mold

k (mold)= 0.5 W/m-K

T (mold) = 353 ^{o}K

Metal properties Cast Iron

ρ =7500 kg/m^3

T_p=1773 ^{o}K

T_m = 1473 ^{o}K

g=9.81m/s^2

Binder properties

ρ_b = 1.31kg/m^3

R_b= 12.31 J/kg-K

Percentage=4%

Additives properties

Dextrin,

ρ_{ad} = 1.250 kg/m^3

R_{ad}=52 J/kg-K

Percentage =4%

Sea Coal

ρ_{ad} = 1.156 kg/m^3

R_{ad} =700.0 J/kg-K

Percentage = 0.5%

Moisture properties

ρ (at 1 bar and 800 ^{0}C)=0.5 kg/m^3

R= 455 J/kg-K

Percentage=6%

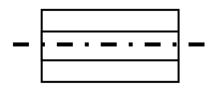
Sand permeability = 100

Coefficient of convection between metal and gas, h=10 W/m^2-^{o}K

Specific heat of Cast Iron, C_m=750 J/ Kg –^{o} K

Results for the gas pressure inside mold cavity (P_{mold}) considering gases escaping through mold walls, time required (τ_i), for layer *dl* to move from one position to next and the temperature of the layer (*Ti*) as it moves up are shown below. Different phases during mold filling are also shown below. The results are tabulated in the table 4.1. The layer at which gas pressure exceeds metallostatic pressure, the color of the filling metal changes from red to green.

4.3.2 Results of Software for Bush (Horizontal Position)



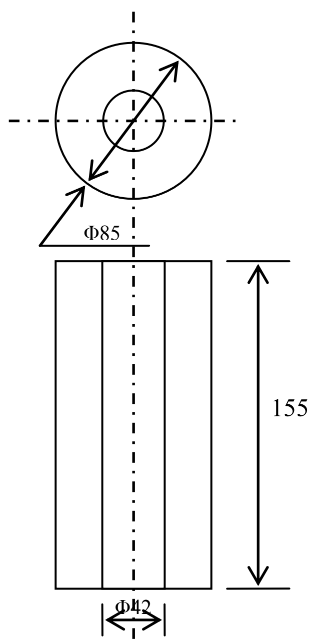


Figure 4.6 Drawing of the bush

Figure 4.5 shows the drawing of the bush with dimensions. Originally, the bush is poured in horizontal position with parting line gating. The results obtained for bush in this position are shown in table 4.1 below. The bush before filling and after filling is shown in the figure 4.7 and figure 4.9 respectively.

Table 4.1 Results for Bush (Horizontal Position)

Position *i* of layer *dl* *i*	Distance traveled by metal layer *dl*, l_i (mm)	Gas pressure inside mold cavity P_{mold} (N/m^2)	Time taken by layer dl to move from *i*-*1* to *i*, t_i (sec)	Temperature of layer *dl* at position *i* *T*i (^{o}K)
1	1	343.2	0.01	1773
2	9	408.535	0.15	1773
3	17	990.503	0.36	1773
4	25	1682.91	0.51	1773
5	33	2217.18	0.64	1773
6	41	2991.06	0.76	1773
7	49	4338.77	0.88	1658
8	57	7263.65	1.00	1559
9	65	16117	1.16	1465
10	73	54302.1	1.39	1331

Maximum metallostatic pressure = 10484 N/m^2

Minimum metallostatic pressure =7425 N/m^2

Minimum temperature = 1278 ^{o}K

Total filling time = 1.65 sec

Discussion

The results show that the gas pressure developed inside the mold cavity is exceeding the maximum metallostatic pressure and there are good chances of blowhole formation in this component. Further, the temperature of the bush is not going below 1000 ^{o}K (solidification temperature for Cast Iron). Therefore we can say that pinholes may not occur in this case.

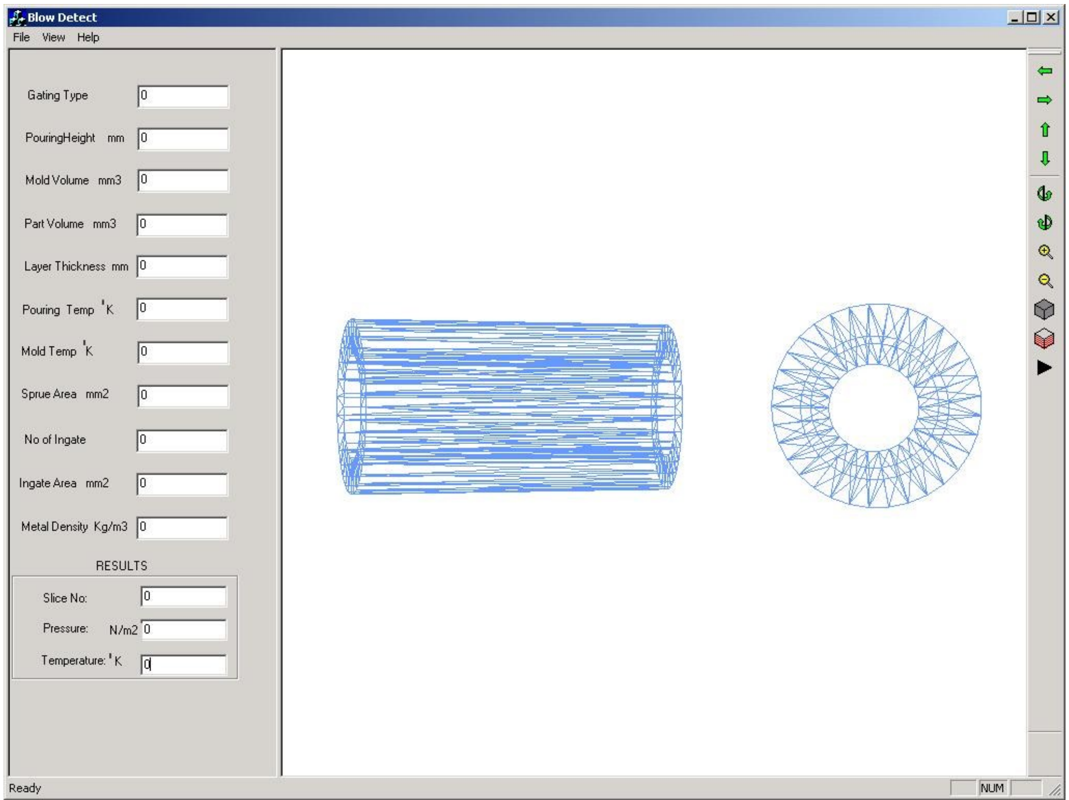


Figure 4.7 Bush before Filling

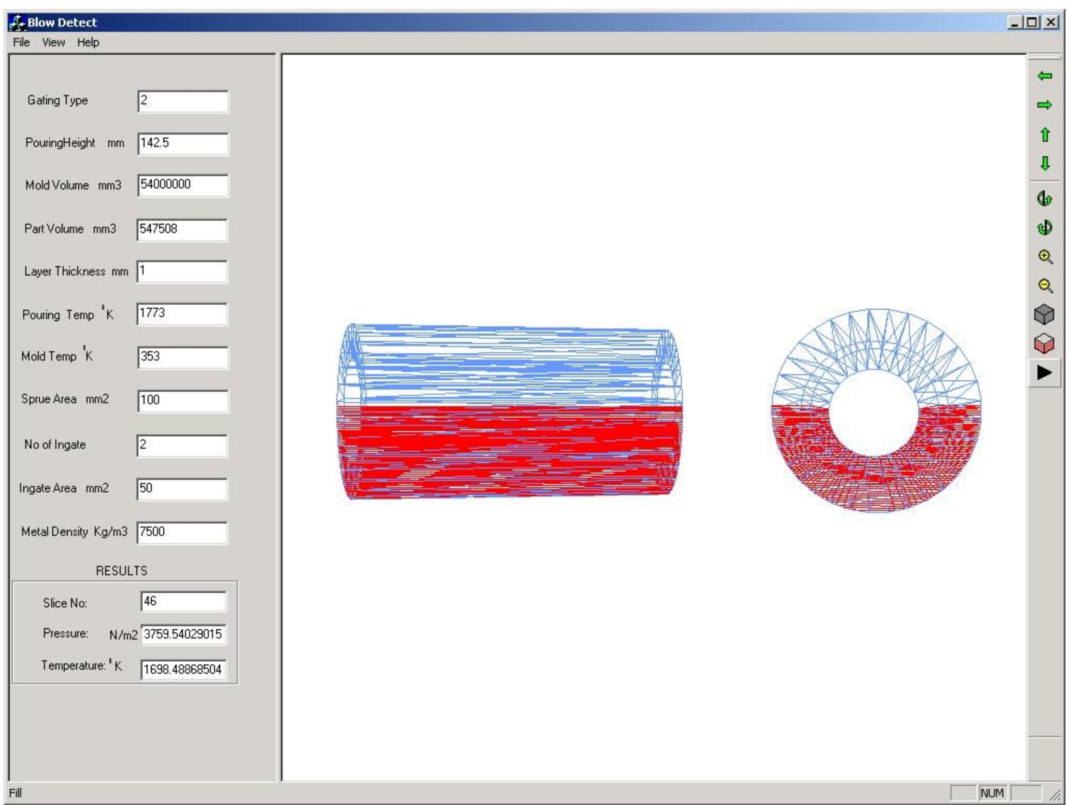


Figure 4.8 Intermediate Stage during Bush Filling (horizontal position)

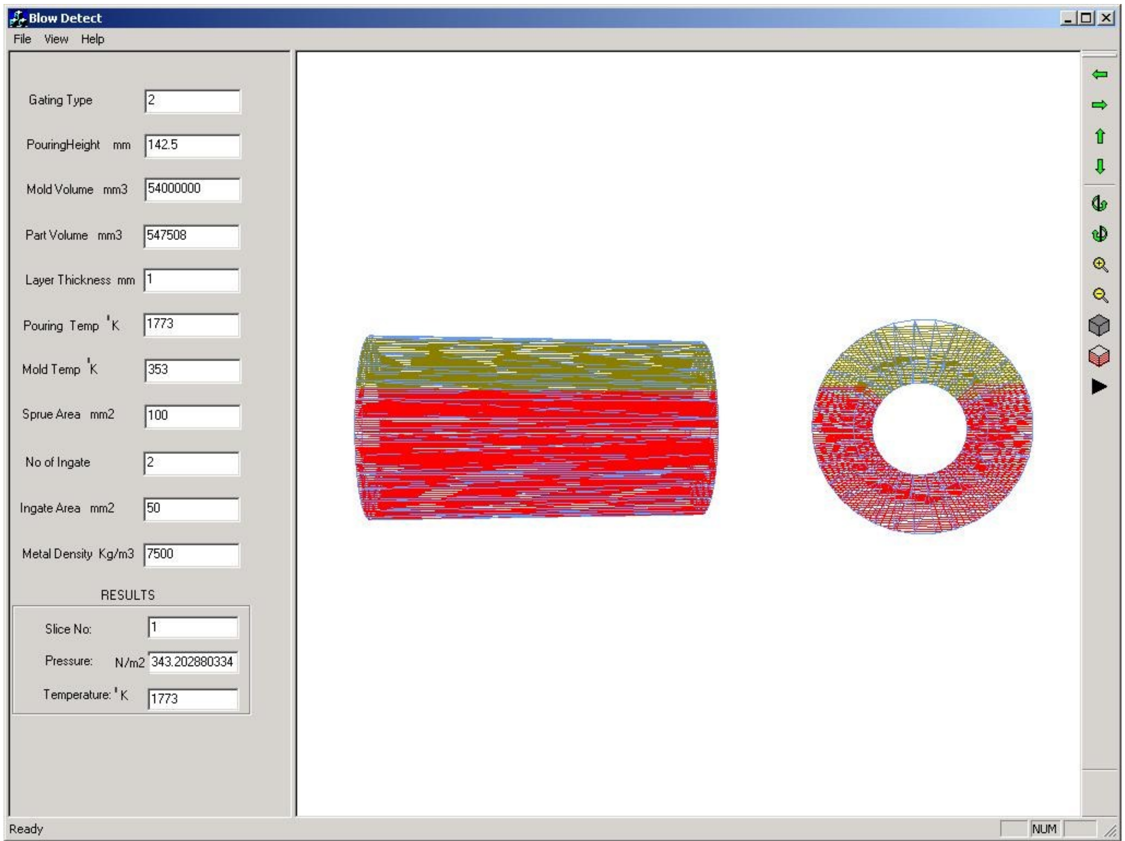
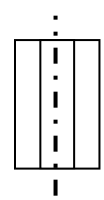


Figure 4.9 Bush after Filling (horizontal position)

4.3.3 Results of Software for Bush (Vertical Position)



In order to see the difference of orientation on results, bush is analyzed for its vertical orientation (axis vertical) with bottom gating system. The results obtained for pressure, temperature and time are shown in following table 4.2. The intermediate stage during bush filling and bush after filling is shown in figure 4.10 and 4.11 below.

Table 4.2 Results for Bush (Vertical Position)

Position i of layer dl I	Distance traveled by metal layer dl, l_i (mm)	Gas pressure inside mold cavity P_{mold} (N/m^2)	Time taken by layer dl to move from i-1 to i, t_i (sec)	Temperature of layer dl at position i Ti (^{o}K)
1	1	139.682	0.01	1772
2	16	318.902	0.15	1771
3	31	554.268	0.29	1771
4	46	878.089	0.43	1771
5	61	1349.75	0.58	1771
6	76	2088.36	0.74	1770
7	91	3362.44	0.89	1770
8	106	5887.88	1.07	1770
9	121	12146.7	1.25	1770
10	136	36186.4	1.43	1770

Maximum metallostatic pressure = 18761 N/m^2

Minimum metallostatic pressure = 7471 N/m^2

Minimum temperature = 1769 ^{o}K

Total filling time = 1.7 sec

Discussion

The results show that the gas pressure developed inside the mold cavity is exceeding the maximum metallostatic pressure and there are good chances of blowhole formation in this component. Further, the temperature of the bush is not going below 1000 ^{o}K (solidification temperature for Cast Iron). Therefore we can say that pinholes may not occur in this case.

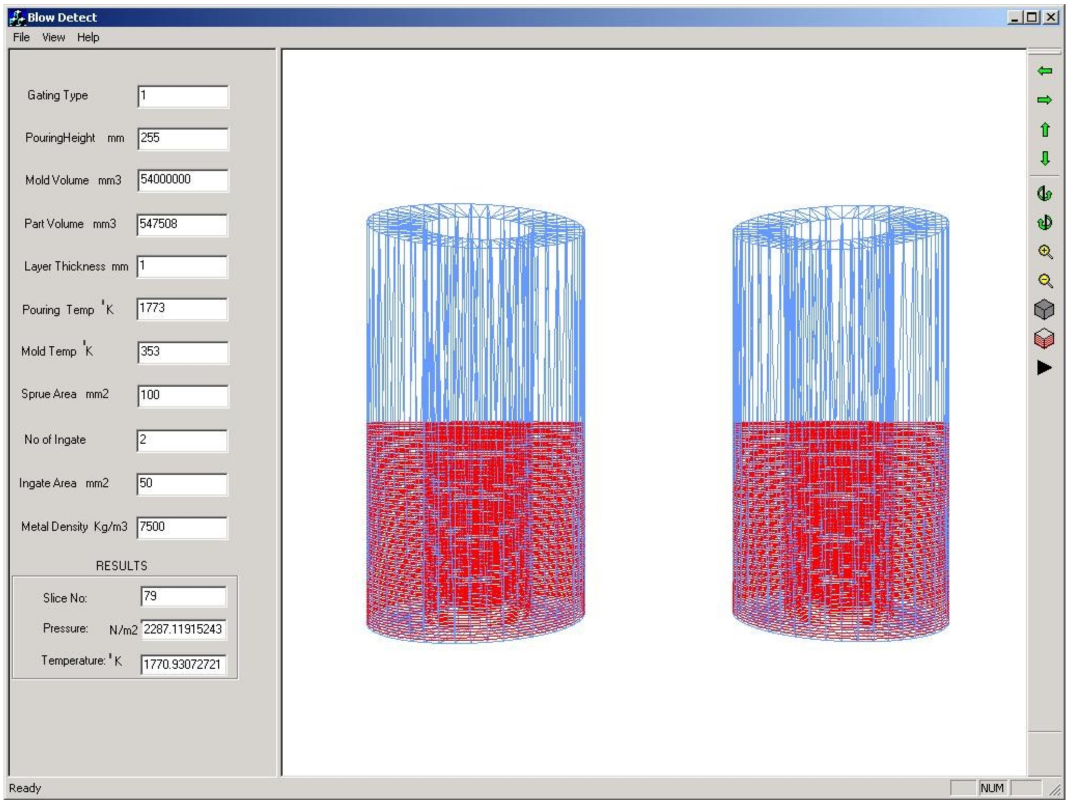


Figure 4.10 Intermediate Stage during Bush Filling (vertical position)

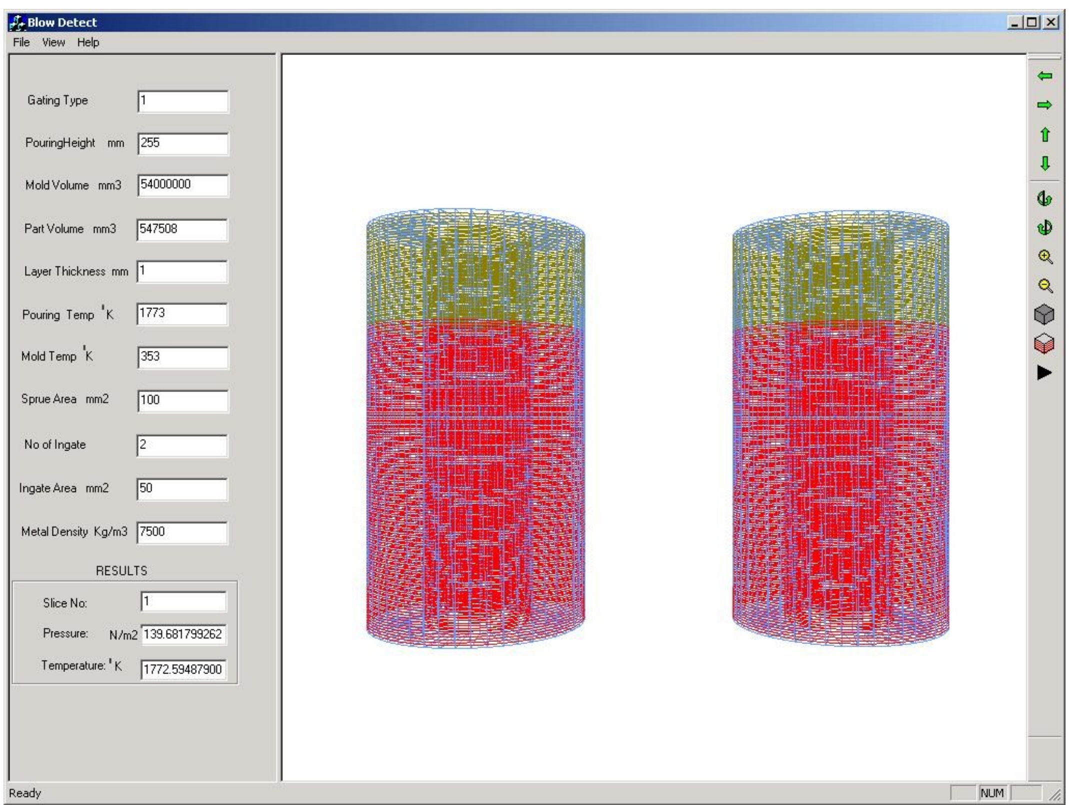


Figure 4.11 Bush after Filling (vertical position)

4.3.4 Results of Software for Pulley

The gating system used for pouring pulley is parting line gating system. The inputs given are same as inputs for bush. Only difference is in pouring height and mold volume. The results obtained are shown in the table 4.3 below. The picture of pulley after filling completely is shown in the figure 4.14 below.

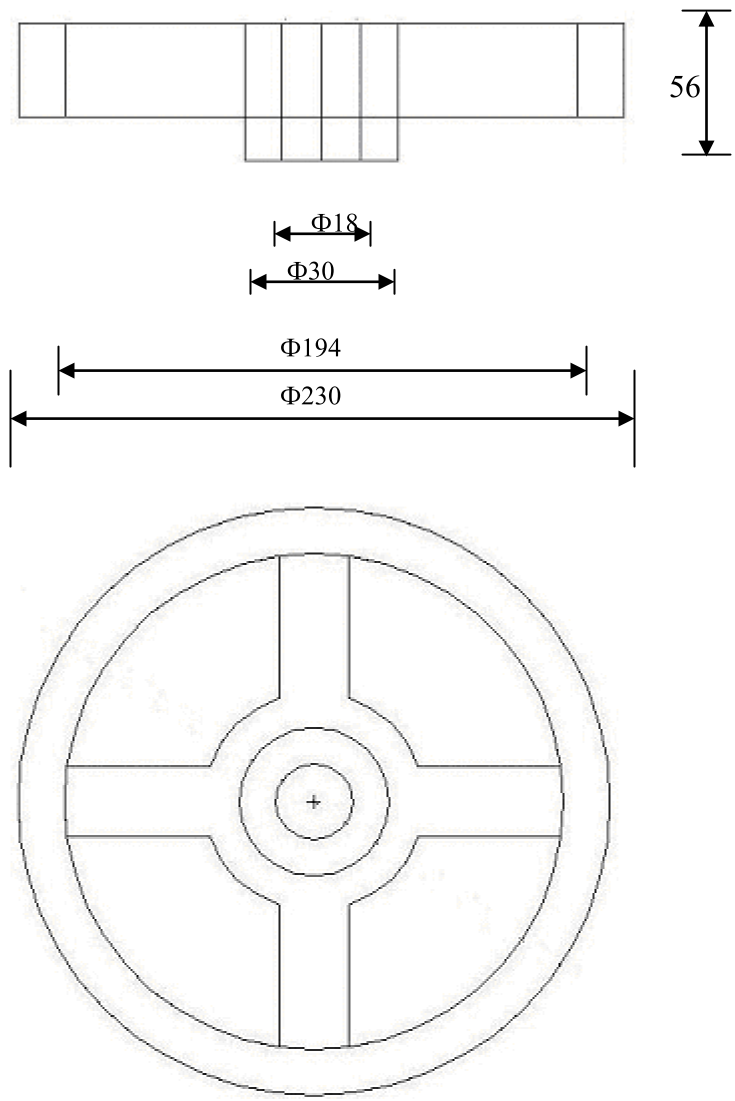


Figure 4.12 Drawing of the pulley

Results

Maximum metallostatic pressure = 9417 N/m^2

Minimum metallostatic pressure = 7523 N/m^2

Minimum temperature = 626 ^{o}K

Total filling time = 1.9 sec

Table 4.3 Results for Pulley

Position *i* of layer *dl* *i*	Distance traveled by metal layer *dl*, l_i (mm)	Gas pressure inside mold cavity P_{mold} (N/m^2)	Time taken by layer dl to move from *i-1* to *i*, t_i (sec)	Temperature of layer *dl* at position *i* *T*i (^{o}K)
1	1	248.332	0.01	1773
2	6	258.124	0.03	1773
3	11	268.371	0.06	1773
4	16	279.1	0.09	1773
5	21	297.493	0.22	1773
6	26	857.417	0.44	1773
7	31	2584.28	2.04	1526
8	36	6777.64	0.68	1316
9	41	22076.2	1.30	1156
10	46	39066.5	1.55	1075

Discussion

The results show that the gas pressure developed inside the mold cavity is exceeding the maximum metallostatic pressure and there are good chances of blowhole formation in this component. Further, the temperature of the bush is going much below 1000 ^{o}K (solidification temperature for Cast Iron). Therefore we can say that there are good chances of pinholes in this case.

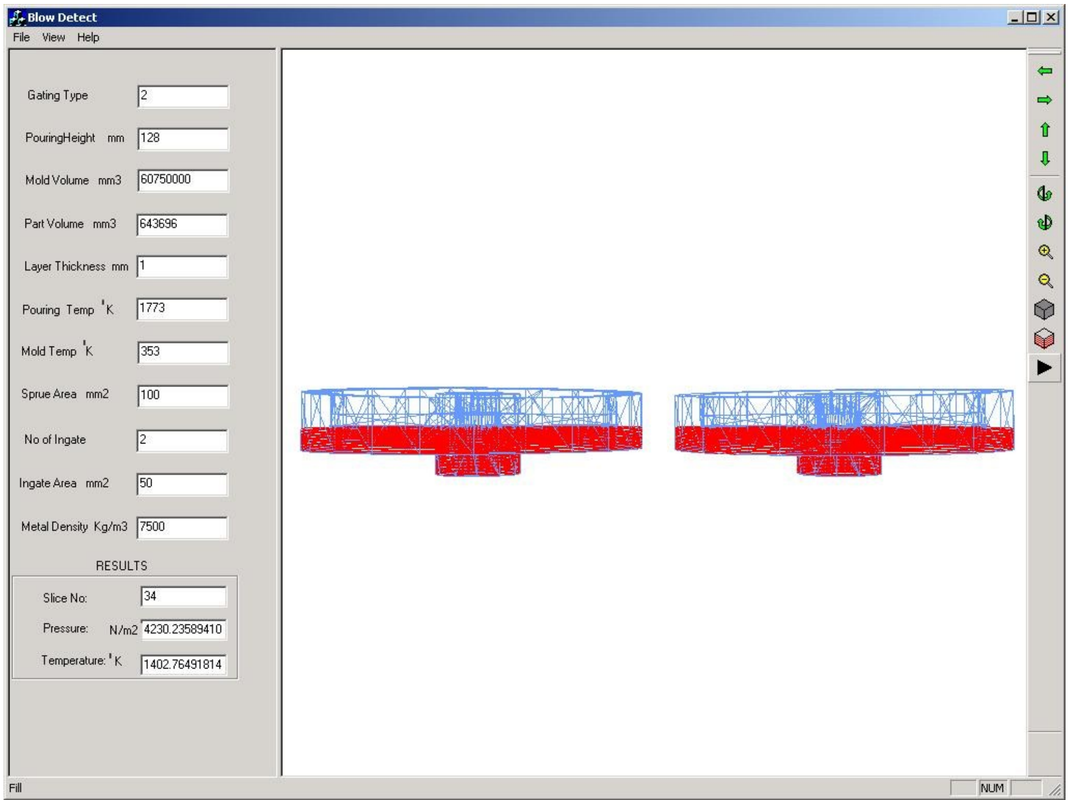


Figure 4.13 Intermediate Stage during Pulley Filling

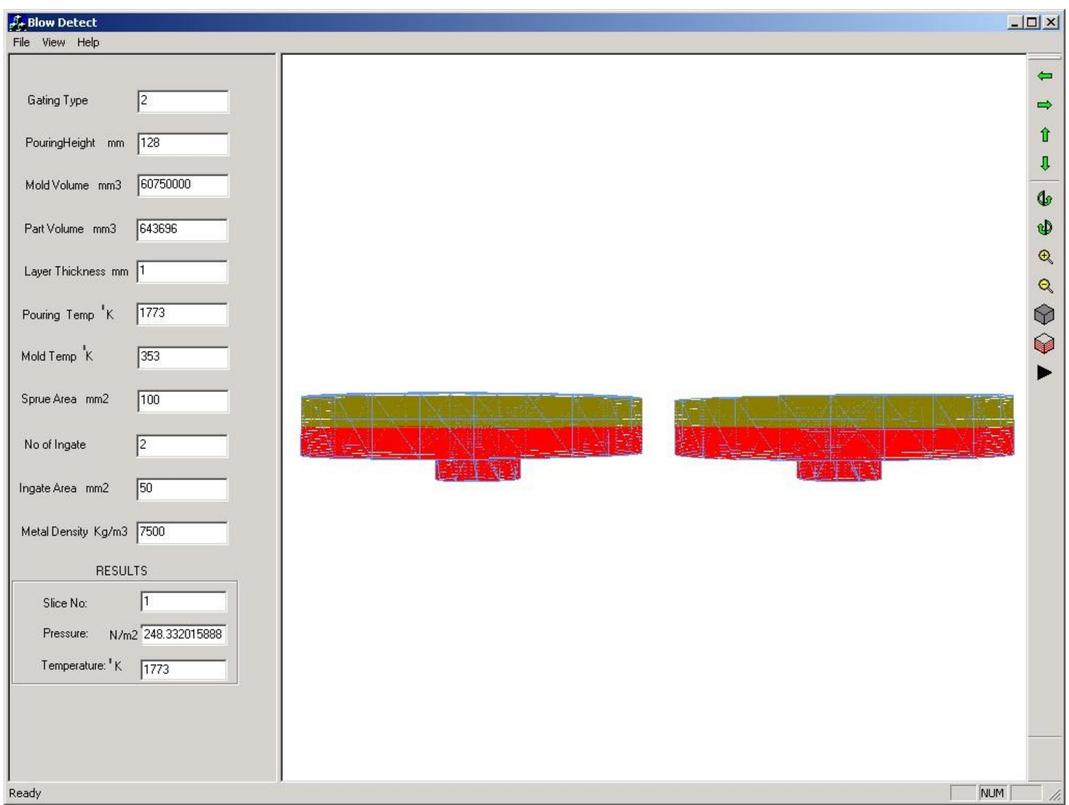


Figure 4.14 Pulley after Filling

Overall discussion

From the results we can see that, the gas pressure inside the mold cavity is increasing continuously as the metal layer moves up. The temperature of the metal layer is dropping till it reaches final position. If we observe the value no10 of all parameters, there is considerable increase in total gas pressure P_{mold} as total gas has not escaped through the mold cavity, volume occupied by gas is very less at this position and practically time required to fill is more due to back pressure of gas acting on metal front than the time shown in table.

When we see the results of temperature for all three components, temperature drop for pulley is very high and practically pulley shows lot of pinholes along with blowholes. Further, for vertical cylinder temperature drop is very less compared to horizontal cylinder, this might be happening due to less area of contact between hot metal and gases in case of vertical cylinder than horizontal cylinder.

4.4 Thumb Rules related to Blowhole

1. In ferrous alloys, hydrogen blowholes have shiny walls, CO blowholes are bluish, and those from entrained air are gray and slightly oxidized
2. If the internal surface of the blowhole is bright and clear the major cause of blowhole is hydrogen.
3. If internal surface of blowhole contains continuous graphite film then cause of blowhole formation is hydrogen and if graphite film is discontinuous then cause is nitrogen.
4. Hydrogen content of the metal should not exceed 1.8 ppm.
5. Nitrogen content of the metal should not exceed 100 ppm, in order to avoid nitrogen blowhole defect. At 140ppm typical fissure like defect but at 320ppm large rounded holes occurs.
6. Cold metal resulting from low pouring temperature is the primary cause of slag blowholes. Pouring temperature should be sufficiently high.

7. The practice of balancing the sulfur content, by adding more manganese should be changed.
8. Manganese level inside the molten metal should be maintained below 0.7 percent.
9. There is optimum moisture content for sand depending upon the proportion of fines and the type of clay used and if this is exceeded then blowholes may be produced. It is up to 4 percent for sands containing fireclay and bentonite.
10. If permeability of sand reduces below 90 blowhole occurs.
11. Use only metallic inserts which are galvanized or copper plated. Carbon content of inserts should be below 0.2%
12. Thin walled castings which are supposed to be filled rapidly are susceptible to explosion and hence blowholes. The same thing applies to smaller castings where metal is strongly agitated.
13. Gating technique is important, as it determines the place where pouring shock occurs and often its magnitude. The pouring shock if not avoidable, then it should be shifted to a place that is not susceptible to explosion.
14. Standard half inch diameter round stock and tapered vent through the cope should be used for castings weighing more than 12kg
15. The smaller pouring shock occurs with tangential gates. Spreading gating system over several places will promote quiet pouring
16. Presence of 0.01 to 0.1% Aluminium in ordinary Grey Iron causes small size blowholes

Chapter 5
Conclusion and Future Scope

5.1 Summary of Work Done

The main focus of the project was on large size blowholes. The project aimed at studying principle, causes and remedies of blowhole formation. Literature review on principle of blowhole formation, causes of gas generation and different ways of reducing their generation in mold cavity was carried out. Mold filling phenomenon and solidification phenomenon taking place inside the mold cavity are studied. Different approaches suggested for blowhole prediction were studied.

We considered layer by layer filling of the mold cavity. Equations are derived for calculating gas pressure during mold filling using Bernoulli's equation. The gas pressure developed inside the mold cavity is compared with metallostatic pressure in order to predict blowhole formation.

It was necessary to consider temperature drop for top moving metal layer during mold filling. Techniques of heat transfer are applied in order to get the equations for temperature drop of the liquid metal layer. Conduction between mold wall and liquid metal is considered. Further, convection and radiation taking place in between metal surface and surrounding gases is considered. Final temperature at the end of mold filling is obtained and compared with solidus temperature of the metal.

In order to analyze any complicated shape, a computer program is developed which reads STL files, slices it along height of the component and calculates area, perimeter, surface area and volume of the STL file. The software developed Visual C++ Version 6.0, using OpenGL.

The software calculates pressure, velocity and time for filling for each increment *dl* of metal layer. Also it compares actual pressure at a particular instant with metallostatic pressure. Further, it calculates the temperature drop for top metal layer, *as* layer moves up during mold filling.

Industrial visits were made in order to collect practical data and industrial components for validating the approach and software developed. The results are validated on simple object with uniform cross section. They are also validated on industrial objects with non uniform cross section along vertical axis using the software.

5.2 Conclusion

Irrespective of whether metal picks up gas as it fills the mold cavity, gas defect will form when gas pressure exceeds metallostatic pressure. The gas holes are not appearing to be affected by composition of gas. The gas holes form at the end of filling and start of solidification.

The software developed is able to handle any complicated shape for analysis purpose. The approach and the software developed for blowhole prediction is able to predict the blowhole formation in sand casting. Further, it gives approximate idea about temperature drop and hence the idea about pinhole occurrence.

5.3 Future Scope of Work

- Getting thermal and physical properties for binders and additives is very difficult. It is necessary to collect values of these properties for all types of binders and additives used in sand casting, so that any sand casting can be analyzed easily.
- It is necessary to calculate the time required to fill considering back pressure of gases acting on metal front.
- We are using approximate approach for temperature drop during mold filling. A neat approach is necessary in order to get the actual temperature drop.

- A system can be developed which uses mathematical modeling and thumb rules both for analysis of blowholes. So that it can consider wide range of possibilities of blowhole formation and accordingly will suggest the required remedies in order to avoid blowholes.
- Slag formation during melting, pouring and mold filling need to be studied properly, which is the major cause of pinhole defects.
- The software can be made more useful by incorporation of mold design, gating design, gating simulation etc.

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Appendix I

A-I Results for Bush (Horizontal Position)

Slice No	Distance (mm)	P_{mold} (N/m^2)	τ_i (sec)	T_i (^oK)
1	1	343	0.01	1773
2	2	409	0.018	1773
3	3	428	0.0314	1773
4	4	427	0.469	1773
5	5	421	0.064	1773
6	6	411	0.083	1773
7	7	406	0.103	1773
8	8	401	0.124	1773
9	9	408	0.147	1773
10	10	419	0.17	1773
11	11	442	0.195	1773
12	12	476	0.221	1773
13	13	520	0.247	1773
14	14	581	0.274	1773
15	15	657	0.302	1773
16	16	749	0.331	1773
17	17	990	0.357	1773
18	18	1171	0.381	1773
19	19	1281	0.402	1773
20	20	1367	0.423	1773
22	22	1502	0.461	1773
23	23	1569	0.479	1773
24	24	1629	0.496	1773
25	25	1682	0.514	1773
26	26	1741	0.531	1773
27	27	1810	0.547	1773
28	28	1873	0.563	1773
29	29	1934	0.579	1773
30	30	1995	0.595	1773
31	31	2060	0.61	1773
32	32	2137	0.626	1773
33	33	2217	0.641	1773
34	34	2298	0.656	1773
35	35	2380	0.671	1773
36	36	2455	0.685	1773
37	37	2543	0.67	1773
38	38	2653	0.714	1773
39	39	2767	0.729	1773
40	40	2876	0.744	1773
41	41	2991	0.758	1773

Slice No	Distance (mm)	P_{mold} (N/m^2)	τ_i (sec)	T_i (^oK)
42	42	3114	0.772	1757
43	43	3245	0.787	1742
44	44	3406	0.801	1727
45	45	3577	0.816	1712
46	46	3759	0.831	1698
47	47	3953	0.846	1684
48	48	4140	0.861	1671
49	49	4338	0.876	1658
50	50	4602	0.891	164
51	51	4898	0.906	1632
52	52	5194	0.922	1619
53	53	5515	0.938	1907
54	54	5864	0.954	1595
55	55	6243	0.97	1583
56	56	6723	0.987	1571
57	57	7263	1.004	1559
58	58	7865	1.021	1547
59	59	8529	1.039	1535
60	60	9232	1.057	1524
61	61	10180	1.075	1512
62	62	11328	1.094	1500
63	63	12625	1.114	1488
64	64	14096	1.135	1477
65	65	16117	1.157	1464
66	66	18826	1.179	1452
67	67	22062	1.204	1439
68	68	27422	1.23	1425
69	69	28871	1.263	1409
70	70	45749	1.295	1394
71	71	54302	1.32	1380
72	72	65240	1.357	136
73	73	79275	1.386	1353
74	74	97672	1.415	1341

A-II Results for Pulley

Slice No	Distance (mm)	P_{mold} (N/m^2)	τ_i (sec)	T_i (^{o}K)
1	1	248	0.01	1773
2	2	250	0.011	1773
3	3	252	0.016	1773
4	4	254	0.022	1773
5	5	256	0.027	1773
6	6	258	0.033	1773
7	7	260	0.038	1773
8	8	262	0.044	1773
9	9	264	0.049	1773
10	10	266	0.055	1773
11	11	268	0.06	1773
12	12	270	0.066	1773
13	13	272	0.071	1773
14	14	274	0.077	1773
15	15	276	0.082	1773
16	16	279	0.088	1773
17	17	281	0.093	1773
18	18	602	0.111	1773
19	19	550	0.141	1773
20	20	171	0.182	1773
21	21	297	0.222	1773
22	22	432	0.263	1773
23	23	576	0.304	1773
24	24	689	0.346	1773

Slice No	Distance (mm)	P_{mold} (N/m^2)	τ_i (sec)	T_i (^{o}K)
25	25	680	0.392	1773
26	26	857	0.44	1773
27	27	1125	0.487	1773
28	28	1420	0.534	1697
29	29	1771	0.582	1632
30	30	2157	0.63	1575
31	31	2584	0.677	1525
32	32	3057	0.725	1481
33	33	3584	0.773	1441
34	34	4230	0.824	1402
35	35	5289	0.888	1358
36	36	6777	0.956	1316
37	37	8643	1.024	1278
38	38	10929	1.093	1244
39	39	13776	1.162	1212
40	40	17389	1.231	1183
41	41	22076	1.301	1156
42	42	27455	1.368	1132
43	43	25872	1.417	1116
44	44	27261	1.461	1102
45	45	32422	1.505	1088
46	46	39066	1.548	1075
47	47	47823	1.592	1063
48	48	59698	1.637	1051
49	49	76375	1.681	1039

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Nitin Bhone