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Methods to Study and Analyse the Effect of Gating System Design on Flow Characteristics: A Literature Review

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ABSTRACT

The effect of mould filling process is significant in determining the quality of casting. The goal of proper mould filling cannot be achieved without proper gating design which influences the flow pattern, further affects the temperature distribution and modifies the progression of solidification. It has been a hot research topic but difficulty in observing the molten metal flow in the gating system and mould cavity due to its opacity and extreme temperatures involved.

Numerical Simulation and Physical visualization and measurements are the two broadly classified methods typically used for study and analysis of flow. To get accurate and dependable prediction of the subtle transient events, one has to make a judicious combination of both methods for a set of casting geometry with an alloy system.

Many researchers used Numerical simulation techniques to analyze the flow through the gating system. While considerable materials are available in literature illustrating the use of Physical methods. Among them Water analogue method to observe the flow of water in a transparent mould is mostly used. Also Direct Observation techniques like Open moulds, Quartz glass window and X-ray radiography were employed, besides using Contact wire sensor method along with computerized data acquisition systems.

This paper comprehensively review the available literature for various techniques to study, analyse and predict the flow behaviour of the melt in order to minimize the related defects arising due to melt flow.

1. Introduction

Casting is the most direct and versatile process of manufacturing in which metal objects is formed by melting and pouring it into moulds. The quality of sand casting predominantly relies on different factors like the melt quality, Methodology for introducing the liquid metal into mould cavity and subsequent metal solidification. The study of filling process is of great significance, for the design of gating system. A well designed gating system should fill the mould quickly, yet quiescently, with minimum turbulence; promote directional solidification; minimize air aspiration thereby reducing re-oxidation and slag formation during mould filling. It should also prevent mould/core erosion and facilitate slag entrapment in the gating system prior to entry of molten metal into the cavity.

Many researchers have tried various techniques which can be broadly classified as computational modelling and physical experimentations [36]. Some researchers attempted to use numerical simulation techniques to predict and analyse the molten metal flow characteristics, which has an advantage to accurately predict the subtle transient events and gain more profound information about the flow behaviour [3-11]. Also, considerable volumes of materials are available in literature describing an efforts made to understand the influence of gating system design on mould filling either by using direct observation techniques like open mould and through a glass window, by real time X-ray radiography to observe the molten metal flow in a sand mould, by using contact wire sensors along with computerized data acquisition, or by water analogy method to observe the flow of water with tracers or coloured water in a transparent mould. This paper attempts to comprehensively review the available literature for various techniques to study, analyse and predict the flow characteristics of the melt, methods advantage and its limitation to analyse the flow characteristics in order to minimize the flow related defects.

2. Literature survey

Different approaches for study, analysis & visualization of flow through the gating systems are attempted by various researchers through decades which had been presented in their research papers. The purpose of this section is to broadly classify & review the current status of research, pertaining to flow study. The existing literature can be broadly grouped as the methods that deal with: Computer Modeling; Water Modeling; Direct Observation; and Contact Wire Sensors methods.

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2.1 Computational modeling

Early in 1965, Harlov *et al.* developed a new technique called Marker and Cell (MAC) for numerical investigation of time dependent flow of an incompressible fluid. Navier-Stokes equations were written in finite difference form with finite time step advancement, while pressure and velocity components were the primary dependent variables. In early eighties (1981) C.W. Hirt developed a concept based on treating complicated free boundary configurations, which was simple yet powerful method called Volume of Fluid (VOF). This method was found to be more efficient and flexible than those existing methods for treating free boundaries.

W.S. Hwang and R.A. Stoehr (1983) suggested the suitability of the approaches of fluid flow modeling useful for different purposes. They suggested the Bernoulli's equation approach and Saint Venant Equation approach to be useful for modeling flow of metal through full channels and partially filled channels, like sprue, runners and in gates, respectively. While Marker and Cell (MAC) technique to be useful for plotting the entry of metal with a free surface into the mould cavity. D.H. St. John *et al.* (1981) adapted a finite element model originally written for flood wave problem for calculating the free surface flow of liquid metals in down runners and gates. Flow patterns predicted by the models were compared with actual flows of metals in sand moulds using X-ray technique and with flow of water in clear plastic systems and further refined the model. K.S. Chan *et al.* (1991) demonstrated a new 3 dimensional technique for handling air-liquid interfaces, as applied to metal casting process. Computations were performed to simulate two distinct filling problems, first dealing with slow filling of a large sand casting mould and other dealing with more rapid situation encountered in PDC and results were compared against water model experiment. Interesting features learnt and analysed from results were surface behaviour such as waves on air voids. Also remedial changes in the casting geometry would able to be introduced to effect improvements. K.Venkatesan (1995) used a numerical model based on FLOW 3D, to simulate the transient, inertia dominated and complex cavity filling in HPDC. To check its accuracy, a comparison with water analogy results from literature was conducted and found to simulate well. Further experiments were carried out to evaluate the effect of gate velocity and fill times on the filling patterns in the dies, which indicated jetting and consequent air entrapments commonly seen even at large fill times. S. Sulaiman *et al.* (1997) carried out simulation of metal along the runner and gating system of PDC with the aid of FORTRAN program to find out the plunger pressure of the injection system during the casting process and to understand the effect of branch angle of the runner and gating system with four gates from 40^o to 90^o. The results showed that the smaller branch angle requires less plunger pressure and needs longer time to fill the system. Further S. Sulaiman *et al.* (2000) made a complete filling analysis by combining the network element method and fluid flow analysis to describe an incremental movement of flow front. They developed 2 dimensional schemes which can provide reliable results like pressure, velocity and temperature variation within the cavity. Paul Cleary *et al.* (2002) described the advances in modeling of casting processes using Smoothed Particle Hydrodynamics (SPH) in HPDC. They compared the simulation results of 2 GDC orientations using SPH and Magma soft, with experimental results from the corresponding Water analogue models. They observed that both the numerical methods were being able to predict the overall structure of filling process, but the natural free surface capability of SPH allows it to better capture the free surface wave behaviour and fine details of the flow. Carlos Esparza *et al.* (2006) presented a methodology for optimization of 3D gating system using FDM programs. They chose two design variables: runner depth and runner tail slope for optimization. The optimization procedure when coupled with casting process simulator enabled them to find a design of better quality. It was also found that starting the optimization with low values of runner depth and high value of runner tail slope yields better designs. Zhizhong Sun *et al.* (2008) proposed a Taghuchi method based optimization technique for design of gating system using Magma Soft. Considering the multiple performance characteristics like filling velocity, shrinkage porosity and product yield, four gating parameters ingate height and width and runner height and width were optimized. ANOVA was used to analyze the effect of gating designs on cavity filling and casting quality and found that runner height and width are the most significant factors contributing more than 80%. Shengyong Pan *et al.* (2010) presented a novel sharp interface for incompressible 2-phase numerical model for mould filling process. The numerical method was to simulate three mould filling examples which were validated with two water filling experiments and one in-situ X-ray imaging experiment of pure aluminum filling. Jun-Ho Hong *et al.* (2012) attempted an optimal gating system design by considering two diagnosis parameters, flow rate difference and arrival time difference of molten metal flow patterns to study the complexity of the runner system using numerical system & comparing it with water analogue test model for a simple plate with eight ingate combinations. From the results the runner system with 2 ingates at extreme ends & sprue at centre has the most ideal results of minimum value of both parameters.

Since physical methods are rooted in the minds of researchers, numerical simulation results have been always doubted due to lack of pervasive validation.

2.2 Water modeling

PD Webster (1967) investigated the flow of metals in runners; in first stage confirmed previous findings of ratio of sprue to runner for aluminum alloys to be in the range of 1:3 to 1:1.5 In IInd stage he studied the flow patterns at the sprue-runner junction using water models as well as sand moulds with fused silica glass window. The study found a considerable contraction of the stream of metal at the point of junction causing suction of gases into metal stream which results in defective casting. F.J Bradley *et al.* (1992) presented a hydraulic based model for calculating the flow distribution the approach used was a pipe-node-path representation of the of the gating system for analysis of complex 3-D configurations. Computer simulations of total flow and flow distribution in a pouring cup plus sprue-runner-2 ingate horizontal gating system were compared with water modeling and experimental results were found in good agreement with each other and with reasonable agreement with previously published molten steel experimental results. Van Der Graaf *et al.* (2001) studied the bottom filling process of a thin, vertical plate cavity. Visualisation experiments of the mould filling process were carried out with water in a Perspex model and with as cast iron and aluminum in a sand mould provided with a glass front. Such observations explored the behaviour of the liquid surface and in case of liquid metals, gave an impression regarding temperature distribution and velocity fields across the cavity. Both CFD results and DPIV provided quantitative data about the surface behaviour and velocity pattern during stages of filling. Although the trends were similar, but the CFD results and DPIV findings do not completely agree quantitatively. Fu-Yuan Hsu *et al.* (2009) proposed a diffusing runner that could reduce the flow velocity under the critical velocity of 0.5 m/s without flow separation from runner wall. A CFD package and water analogy method was employed for exploring and verifying the new designs. The efficiency of the diffuser was quantified by measurement of coefficient of discharge Cd. Analysis of results showed that, Kinetic energy hadbeen efficiently transformed into pressure head through this diffuser while preventing the harmful oxide films and bubbles. M. Afsharpour *et al.* (2014) investigated the effects of pouring basin and sprue design on bubble entrainment phenomena during pouring and moulds filling using several transfer water models of gating system which were imaged and subjected to computer image analysis. The results accomplished that the base design was of barrier basin. While other recommendations for sprue design was, reducing sprue diameter and a slope for a sprue well for reduction of bubble entrainment. K.H. Renukananda *et al.* (2012) in his initial paper made a comparison of discharge through multiple gate horizontal runner using Nova soft simulation and water modeling setup with centre sprue and slide sprue arrangement. The results matched with the previous literature trends of discharge and also established the ratio of discharge between the different gates. K.H. Renukananda (2013) the authors compared the flow of water and LM6 aluminum alloy using numerical simulation and water models to investigate the effect of number of gates open on the total discharge across various combinations of open gates and found different for each combination. It was concluded that while both metal and water flow showed similar trends, the volumetric flow to molten metal was about 1.7 times that of water. As in previous studies K.H. Renukananda *et al.* did not validated result with actual metal flow experiments. In this paper (2015), he investigated to check the validity of water models for understanding the flow of liquid metals. Three fluids were considered for experiments: Al-Si alloy, zinc and water with the parameter of interest were flow sequence, velocity and discharge through four gates. It was found that the proportion of flow through the four gates found to be nearly same for all three fluids, while the first gate filled first and the last gate had maximum discharge volume. The results established the usefulness of water models to investigate mould filling in metal casting and provided valuable insights for balancing the flow through multiple gates. V. Jaiganesh and K. Prakasan in his initial paper (2013) concerned their work with the hydraulics and flow characterisation in the pressurized, horizontal gating system using water models applied scaling factors for length and scaling to obtain maximum similitude with real casting. Flow behaviour was visualized in downsprue, runner, in-gate and mould cavity using water model and real casting in sand moulds. By comparing the difference in flow behaviour in both approaches, they found that the flow becomes less turbulent with increase in aspect ratio and also reduction in pouring height can control mould entry velocity. In ability of water model to predict the possibility and degree of turbulence was also observed. V. Jaigenesh and K. Prakasan (2015) the author studied the influence of hydraulics and geometric variables on discharge variation across the gates using Taghuchi technique. The factor selected were metallostatic head, runner aspect ratio, Gating ratio and types of gates. ANOVA was applied to determine statistically significant factors and their percent contribution and found that Gating ratio was having a maximum influence on discharge variation.(followed by runner aspect ratio, head and type of gate).In their latest paper V. Jaiganesh (2016) investigated the hydraulics and flow behaviour of an aluminum alloy. They conducted their experiments in two parts using runners and 2 ratios and four types of ingates Flow measurement experiments were conducted to measure the discharge and velocity through each ingate and understand the influence of hydraulic and geometric variables. Flow visualization experiments were conducted for direct observation of flow behaviour in critical sections of the gating system and mould cavity using water modeling and real time experiments with molten metal in sand moulds. Comparison of filling pattern provided a useful insight into the performance of gating system. It found that the transport of turbulence into runner is inevitable for all runner aspect ratio, but can be minimized by using wide and shallow runner. It was also observed that during major portion of fill time the entire cross section of gates was not utilized, which could to air aspiration.

Water modelling techniques restricts to only qualitative analysis of flow & difficulty in making model complex castings are challenges.

2.3 Direct observation:

J. Runyoro and Prof. J. Campbell (1991) investigated the efficiency of various sprues' moulded in sand by demonstrating maximum allowable ingate velocity by video recording the direct observation of metal emerging from vertical ingates moulded in sand. They tested velocities from 0.1 to 2.0 m/s and found that at 0.50 m/s metal emerges from ingate by simple flooding without leaving the mould wall contact, while at 0.85 m/s mushroom jet formation was observed. It was also found that drag co efficient was minimum when sprue taper is approx. twice of theoretical. S.M.H. Mirbagheri *et al.* (2003) compared experimental results of casting of aluminum alloy with transparent mould to verify the developed mathematical model based on SOLA-VOF technique which was modified to take into account the effect of gas pressure and coating permeability during filling stages of mould cavity. M. Masoumi *et al.* (2005) studied the effect of gate geometry and size on the flow pattern by pouring molten metal of aluminum alloy into a sand mould. Direct observation by fixing a grid glass in the cope was used for video recording and was furtheranalysed by computerised system. The result showed that an increase in width of gate with constant thickness resulted in three different patterns of metal front as narrowing, expansion and deviation. Niels Skat Tiedje *et al.* (2011) investigated the factors that control velocity in different parts of the gating system, with a focus on local pressure in the gating system. For analysing how the gating system geometry influences the pressure field in the liquid. They used the combination of direct observation experiments and numerical modeling to analyse how pressure waves are formed and how they influence the melt flow in the initial phase of mould filling. They found that the filling time and flow pattern compare well, but was different from free surfaces. Zhao Haidong *et al.* (2008) established a mould filling simulation

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model, taking into account the mass, momentum and energy transfer within free surface elements to describe its shape and location. The simulation results were compared and verified with X-ray observation of actual mould filling process of the casting where the liquid flowing in the runner and ingate as well as evolution of free surfaces were analysed. They found that when using pressurized feeding system and sand mould with good air permeability, back pressure of gas in the mould cavity has minor effect on changing the liquid metal flow. Mark Jolly *et al.* (2009) investigated the L-Shaped junction in running and gating system using aluminum gravity casting using computational modeling. They conducted a three part experiment in which the first and the second part they explored 2-D and 3-D model of L junctions. In the final part, a 3-D L junction geometry was constructed with in a runner system and casted under an x-ray facility for its validation and studying the filling sequence of runner system. They quantified the efficiency of sprue runner junction by measuring co efficient of discharge C_d. The value of C_d for a single gate system was quantified as 0.70, while for multiple gate was to be 0.68, indicating the casting fill time to be 1.43 times longer than friction free condition and 30% overall frictional loss. Zhao lei *et al.* (2011), attempted an in-situ observation of porosity formation during directional solidification of two Al-Si alloys at near eutectic (13% Si) and hypo eutectic (7%Si) by using a micro focus X-ray imaging. Observation of porosity formation was conducted in the X-ray temperature gradient system (XTGS).

However, direct observation methods is still limited for experimental study of 2 dimensional shapes only. Also critical restrictions of size, thickness, expense, & safety limits the use of X-ray radiography.

2.4 Contact wire sensor method

S.H. Jong and W.S. Hwang (1992) demonstrated the contact time technique to study the filling phenomena in two industrial castings in order to get information regarding the filling sequence, ratio among multiple ingates and the last filled areas, which are important to evaluate the appropriateness of the running/gating system and to verify the accuracy of theoretical predictions of the mathematical modeling techniques. They also developed software to transform the measured contact times into graphical patterns. It was also noted that this method is more suitable for castings of thin sections due to sensor wires were recommended to be inserted near the mould surface in order not to interfere with melt flow. Laurence Gaston *et al.* (2000) presented a 2-D finite element approach for a non steady turbulent fluid flow with free surface, based on a velocity-pressure finite element Navier-Stoke's solver. They made 3 comparisons between numerical results and experimental results to illustrate the efficiency of this approach. The first one was with the presented approach and its validation with the second one in a mould filling in effective casting conditions and the third one with the help of water modeling. In the experimental work, a 3-dimensional mould equipped with contact sensors. The contact sensors were activated when the metal touches them and the activation time was recorded and the flow advance was tracked. J.H. Kuo *et al.* (2003) developed a mathematical model to simulate the filling pattern in LFC and validated by comparing the results with the experiments conducted with thermocouples embedded in the pattern of LFC by measuring the temperature data and filling pattern. In temperature measuring and recording system, the progress of the molten metal front inside the pattern was monitored by inserting a probes of K-type thermocouples (0.18 mm Dia.) surrounded by a ceramic tube (2 mm OD), which were connected to data acquisition system. The four thermocouples located at strategic locations detected the contact time of the metal front, indicating the sequence of metal front and cooling during solidification. J. kang (2003) developed a measurement system for the liquid metal filling based on modified contact time method (MCTM). The filling of measured points was illustrated by a LED pattern and the filling time of all the points for analysis were obtained by recording a video. The method wasfree of limitation of signal acquisition channels, thus the filling at 100 positions ware measured and the filling profiles and filling velocities were obtained, which reflected the features of its filling process. They investigated the influence of some parameters like metallostatic head, density of EPS pattern, thickness of casting and permeability of sand mould on the filling process. The results showed that the front moves forward by the effect of initial speed and gravity during filling the area below the ingate. Above the ingate, the filling was stable, but slower than the lower half. It was also found that both height of sprue and the coating thickness have strong effect on the filling process. J. Kang *et al.* (2013) developed a wireless measurement system for filling process of the casting based on contact time method and an observation system based on high speed camcorders working under high temperature. By using these 2 systems, they observed and measured the filling process of a turbine blade and hub castings. The velocity of the liquid steel in the mould was obtained by the calculation of filling time. The study showed that the two systems operate conveniently and reliably, also are effective tools for monitoring the filling process of the castings and future optimizing of the gating system.

Since the wires & cables may cause trouble on site, application of this technique is not suitable for casting production.

3. Critical survey

A large number of investigations linking gating parameters with casting quality have been carried out by researchers and foundry engineers over the past few decades. A lot of efforts have been made to understand the influence of gating systems design on mould filling using various techniques. Computational modeling and physical experiments are the most commonly used for it. But it is important to verify computational model of mould filling with physical experiments. Numerical simulations have been widely used in research and production. However, the simulated results are been doubted due to lack of validation. As physical models are rooted in the minds of researchers, so they had attempted different methods to investigate the flow characteristics. Among them, water analogy was used for investigating flow characteristics of simple castings. The advantage is that the flow pattern is clearly visible in all parts of the gating system and mould cavity. An open mould or a temperature resistant transparent quartz glass window can be used to observe the melt flow. This method is most suitable for experimental study of thin section cast specimen. Development of high intensive X-ray provided a new method of using X-ray with high speed camera to capture the mould filling sequence in an opaque sand mould. This method is suitable for experimental study, but is limited by casting size and thickness, expenses, & safety issues.

Also contact time method where a set of sensor wires connected to a circuit detects the melt flow front & calculate the filling speed. The temperature of the metal can also be detected using thermocouples wrt. time and solidification rate as well as direction can be determined by connecting it to computerized data acquisition system, but too many wires may cause trouble in production.

To get accurate and dependable prediction of the subtle and transient events, one has to make judicious combination of computational modeling and physical experiments to predict and analyse the behaviour of the molten metal through the gating system. This will give an advantage of being able to study the internal flow and gain more profound information about the behaviour of the melt stream.

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