Optimization of Multi-Gate Systems in Casting Process: Experimental and Simulation Studies

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Abstract. This paper proposes an improved gating system design for casting process using experimental and simulation studies. The principle motivation behind optimization of gating system is to overcome the defects like shrinkage, gas porosity, slag, inclusion, cold shuts and misruns etc. Four different designs having different sprue location and runner cross-sectional area are taken into considerations for study. Discharge through multiple gates which are connected to horizontal runner has been evaluated as a performance parameter for comparing the designs. Experiments are conducted by tap and collect method using water and the volume of flow through each gate is observed for all designs. A simulation-based study is carried out for all four designs on finite-volume commercial code FLUENT. Boundary and initial conditions, such as velocity, pressure, temperature, etc., was reasonably set. It is found that the flow rate, as well as average velocity through the farthest gate, is higher for the parallel runner while this difference gets reduced with a tapered runner. Furthermore, design with a central position of sprue also minimizes the difference in flow rates as well as velocity. Finally, a design with a tapered cross-sectional area and justified position, as well as orientation of different gates, is finding out to be optimum having balance flow rate through the four gates with less filling time.

Keywords: Casting, runner, gates, flow velocity, flow rate.

1. Introduction

In casting process, gating system plays vital role to produce a good quality casting. A gating system controls mould filling process as well as flow pattern in the gating system. Multiple gates are required to ensure proper distribution of flow along with sufficient temperature. In general, different sections of a casting are required to fill at approximately the same flow rate and fill time. This will lead to similar conditions for solidification, and thereby less variation in mechanical properties. The main function of gating system is to lead clean molten metal from ladle to the casting cavity ensuring uniform, smooth as well as complete filling of mould. The design of the gating system depends on the number, size as well as shape of the casting, to ensure uniform metal flows to all sections while maximizing the casting yield. The
rate of flow of metal is regulated by the smallest cross section referred to as choke, which is typically at the bottom of sprue or the gates. The ratio of cross-section area of sprue bottom, runner, and gate, which is called the gating ratio, affects the rate of molten metal flow in various sections of gating system.

To study the fluid flow through gating systems and to evaluate their design, three approaches have been adopted in casting industry. These are: (1) empirical relations derived from experimental observations, (2) hydraulics based analysis involving Bernoulli’s and continuity equation, and (3) numerical simulation involving solution of the mass and momentum conservation relations. Two basic assumptions have to be made before hydraulics can be applied to gating problems. The first is that all molten metal poured remains liquid until filling of mold cavity is completed and second one is that the molten metal behaves like true liquid. With this background a systematic study is taken up in which physical models of gating system are made up of acrylic and water is used in place of molten metal.

Complete similitude between real time casting and water model experiments is met so long as certain non-dimensional numbers are same in the both case. These numbers are Weber number, Reynolds number, Froude number and Euler number. Experiments have revealed that Weber number is very insignificant in gravity casting since surface tension plays very much less role. While Euler number is predominantly used in pressure die casting where pressure difference is imposed upon metal by some external element. In gravity casting, flow is assisted by gravity. Hence such situation is not arising. The relevant non-dimensional numbers in water model experiments are found to be Reynolds number and Froude number. If the both number are equal, then condition of physical similarity is met and maximum similitude is achieved. The conditions to ensure analogy are:

\[ Re_1 = Re_2 \quad \text{and} \quad Fr_1 = Fr_2 \]

From the above two equations, we can conclude that the similitude is greatly influence by the kinematic viscosities of different fluid used in model and the real casting.

| Table 1: Properties of aluminium and water |
|------------------------------------------|
| Liquid       | Temperature(°C) | Density (gm/cm³) | Dynamic viscosity(centipoises) | Kinematic viscosity(centistokes) |
|--------------|----------------|------------------|-------------------------------|--------------------------------|
| Water        | 20             | 1                | 1                             | 1                              |
| Aluminium    | 700            | 2.37             | 3                             | 1.27                           |

The kinematic viscosities of aluminium is similar to that of water, and full scale water models of gating systems and cavities for Al should therefore give a good indication of flow conditions in the actual castings.

The literature review is mainly focusing on design and optimization technique based on casting related defects and their research and outcomes. This includes the development of mathematical models of flow in gating systems, based on experimental observations. In one of the earliest such studies, it was concluded that the farthest gate from the sprue exit had the largest flow of molten metal. It was reported that the flow in runner is largely independent of the length of runner between the gates [1]. Martin [1] reviewed the work of different researchers on gating ratios and concluded that the selection of the most appropriate gating ratio is influenced by the formation of dross and metal impingement against mold walls and cores. Other researchers [2], [3], [4] proposed methods to determine the relative flows from different gates by determining the losses in the channel flow. In general, it has been observed that the simulated filling sequence is somewhat different from experimental observations [5]. In one study, while water model experiments were observed to be useful for comparing simulation results, it was concluded that software simulation cannot entirely replace actual experimental work [6]. In another work, comparison between simulation and experiments, it was found that due to wall friction and surface tension the shape of liquid
front was different between the both [7]. F. J. Bradley [8] derived an energy balance equation for each path and a continuity equation at each node were applied for the whole system and solved for simultaneous algebraic equations to predict flow rates in each segment. Ravi and Joshi [9] worked on Auto-CAST software and they describe how it assists in designing, simulating, modelling, analysing and improving cast products properties. Bhatt and Barot [10] reported that the design optimization of gating system and simulation reduced the casting defects. Masoumi et al. [11] reported the effect of gating design on mold filling for casting processes. The validation results showed that the design as well as shape of the gate and the gating ratio have a great influence on the pattern of mold filling. Sutaria [12] worked on a new idea where optimization of casting feeding is done with the help of feed-paths. Literature on optimization of gating system recommends minimizing the in-gate velocity of melt, maximizing the yield, minimizing warpage and optimizing location of in-gate. This work focuses on the maximizing the filling rate and minimum difference in flow rate as well as velocity through in-gates. Higher filling rate is useful to increase the production rate of castings. Higher filling rate is also required in thin and long castings which lose heat very rapidly.

2. Methodology

2.1. Water Modelling

Many researchers have studied fluid flow in gating systems and mould cavities with the aid of transparent models usually made of Perspex or other plastics, in which the flow of metal is simulated by that of water. This method has the substantial advantage that the pattern of flow is clearly visible in all parts of the gating system and the cavity, but its validity, depends entirely upon the correctness of the assumption that the flow of water is closely analogous to that of the molten metal.
Table 2: Detailed specification of considered four gating system designs

| Design  | Runner     | Runner’s Dimensions       | Sprue Position | Gates Position w.r.t. sprue |
|---------|------------|---------------------------|----------------|---------------------------|
| Design 1 | Parallel   | Ø 2 cm throughout length  | At end         | All four on one side      |
| Design 2 | Parallel   | Ø 2 cm throughout length  | Central        | Two-two on both side      |
| Design 3 | Tapered in one direction from one end to other | Ø 2 cm at one end & Ø 1 cm at the other end | At end         | All four on one side      |
| Design 4 | Tapered in both direction from centre | Ø 2 cm at centre & Ø 1.3 cm at both end | Central        | Two-two on both side      |

According to the theory, a water model of gating system and cavity should accurately reproduce the character of (steady-state) flow of a metal in the corresponding sand-moulded gating system and cavity, provided that the Reynolds number in the two cases are about equal. Reynolds number is dependent on the diameter of the flow channels and on the kinematic viscosity of the liquid, and is therefore of interest to compare the kinematic viscosities of liquid metals with that of water and other fluids.

The dimensions of gating systems used in water model experiments are calculated using simple relationships. The design of a gating system begins with the selection of the appropriate gating ratio and the alloy for which the study is proposed to be carried out. Popular gating ratio for an alloy of aluminium is 1:4:4. So gating ratio of 1:4:4 is chosen to illustrate the design procedure.

2.2. Simulation Study

The whole filling process for each considered design were simulated using ANSYS 16 fluent to determine the optimum one. It was based on a transient 3D situation. Used material for simulation was aluminium and used properties for simulation was listed below. Before initializing the whole model, required conditions were being applied. Since, we only wants to focus on the flow behaviour of the molten metal, therefore the energy and viscous model were used to simulate the flow. Simulation was run for 250 iterations with 10000 mesh size for each design concept under the same conditions. Whole filling process was considered to be as gravity casting. All the properties used were listed as bellow.
Figure 2: Acrylic model for water modelling of considered four Gating Systems.

### Table 3: Parameters taken for simulation study

| Mould’s Material | Metal Used     |
|------------------|----------------|
| Green sand       | Aluminium      |
| Density          | 1.5 g/cm³   | 2.375 g/cm³ |

### Table 4: Aluminium properties

| Property               | Value |
|------------------------|-------|
| Pouring temperature    | 900 °C |
| Melting temperature    | 660 °C |
| Viscosity(stokes)      | ~ 0.0012 |
3. Results and Discussion

3.1. Water Model

Figure 3: 3D ANSYS model for simulation of considered four Gating Systems.
Flow rates and flow velocities through different gates were calculated using tap and collect method. Central position of sprue minimizes the difference in velocities as well flow rate from the gates which is required for a good casting. Tapering of runner further minimize the difference. Hence we can observe that design 4 would be the best one for optimum casting conditions.

3.2. Simulation Model

Results from the simulation studies show the similar trend as observed in water model experiments. Design 4 comes out to be the optimum one. Molten Aluminium behaves same as water.

3.3. Modification of design
To further optimize the gating system design, some modification has been done on design 4. Sharp bends had been replaced by acute angle joint to facilitate streamlined flow. Due to this modification, losses due to bend has been minimized and streamlined as well as uniform flow of liquid has been achieved.

Figure 6: (a) Modified acrylic model, (b) & (c) 3D ANSYS model of modified design used for simulation.
Figure 7: Velocity profile at bends (a) before (b) after modification and at sprue exit (c) before (d) after modification

Table 5: Flow parameters for the modified design through water model

| Modified Design | Average flow rate (mL/s) | Average flow velocity (m/s) |
|-----------------|--------------------------|----------------------------|
| Gate 1          | 42.23                    | 0.537                      |
| Gate 2          | 39.20                    | 0.494                      |
| Gate 3          | 39.18                    | 0.498                      |
| Gate 4          | 41.80                    | 0.532                      |

4. Conclusion

From the above study, we can conclude following:

1. The location of gate in multi-gate system as well as junction nature i.e. how the gate is attached with runner (whether a sharp bend is there or a smooth bend) beside of runner cross-sectional area also affect the flow parameters.
2. From the flow measurement experiment, we find that to maintain constant pressure throughout the runner, we have to reduce the cross sectional area in direction of flow. So by locating the last gate at the end of runner would increase the casting yield.
3. The flow rate from the four proposed designs of gating systems, design 1 and 3 are highly varying whereas design concept 2 and 4 gives somewhat uniform flow rate hence on the basis of flow rate criteria design 1 and 3 comes out to be worst while 2 and 4 gives more satisfactory results.
4. Hence design concept 4 fits best in both the deciding criteria i.e. flow rate and velocity at ingate. Further some modification have been done in the design concept 3 to avoid the high erosion at the bottom of sprue and negative pressure at sharp bends.
5. Simulation studies also shows very much similarity in the trend of flow rate as well as flow velocity with water model. In addition, variation between the both can be attributed to the different properties of considered fluids.

6. Simulation of this modified version of design concept 4 gives better results as shown below.

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