Defect and Diffusion Forum Vol. 344 (2013) pp 43-53 Online: 2013-10-11
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doi:10.4028/www.scientific.net/DDF.344.43

[6] Numerical Investigation of the Effect of Sprue Base Design on the Flow Pattern of Aluminum Gravity Casting

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Keywords: Computational Fluid Dynamics, Gravity Casting, Sprue Base Design, *Vena Contracta*

Abstract

Effects of sprue base size and design on flow pattern during aluminum gravity casting have been investigated by employing different sprue base sizes and using computational fluid dynamics (CFD). Calculations was carried out using SUTCAST simulation software based on solving Navier-Stokes equation and tracing the free surface using SOLA-VOF algorithm. Flow pattern was analyzed with focusing on streamlines and velocity distribution in sprue base, runner and in-gate. Increasing well size was produced a vortex flow at the bottom of sprue base which increased the surface velocity of liquid metal in runner. Using a rather big sprue well could eliminate *vena contracta*, but in-gate velocity was observed independent from well size. It assumes that in-gate velocity may be more influenced by other casting considerations. Using a curved sprue base could remove vortex flow at the bottom of sprue while keeping a nearly full contact between liquid metal and runner wall.

1. Introduction

A most important aspect of production of clean and sound castings is the method by which the molten metal is introduce into the mold cavity. One of the running and gating system duty is to ensure that the flow of metal should be as free as possible from turbulence but at a rate sufficient to avoid undue delay in filling the mold[1]. Surface turbulence promotes entrainment oxide films inside the cavity. Oxide films play a major role in the control of mechanical properties which are affected by gating system design. Liquid aluminum contacts the surrounding atmosphere containing the oxygen and has a tendency to form an insoluble oxide film on the surface. Oxide cracks formed as a result of surface turbulence or bubble trail damage, and cause uncertainties in the static strength of castings. The application of process control has been suggested to avoid such uncertainties and to ensure that such defects are not introduced in the first place[2].

There is a critical velocity at liquid metal front which is high enough to push the metal surface but its inertia pressure is smaller or equal to surface tension then any perturbation could be avoided in this condition. For example the critical in-gate velocity for liquid aluminum was determined as $0.5 m.s^{-1}$ by Runyoro[3] and higher in-gate velocity cause surface turbulence and generates severe rates of oxides entrainment. In an emphatic research Grube and Kura[4] have investigated water flow through the transparent mold using a high frame per second camera. Maximum velocity of 0.457 $m.s^{-1}$ at the exit end of the gate has been captured and later while pouring liquid aluminum with 7% Mg at the same running system no surface defects was observed in final product. Green[5] has found that high- reliability

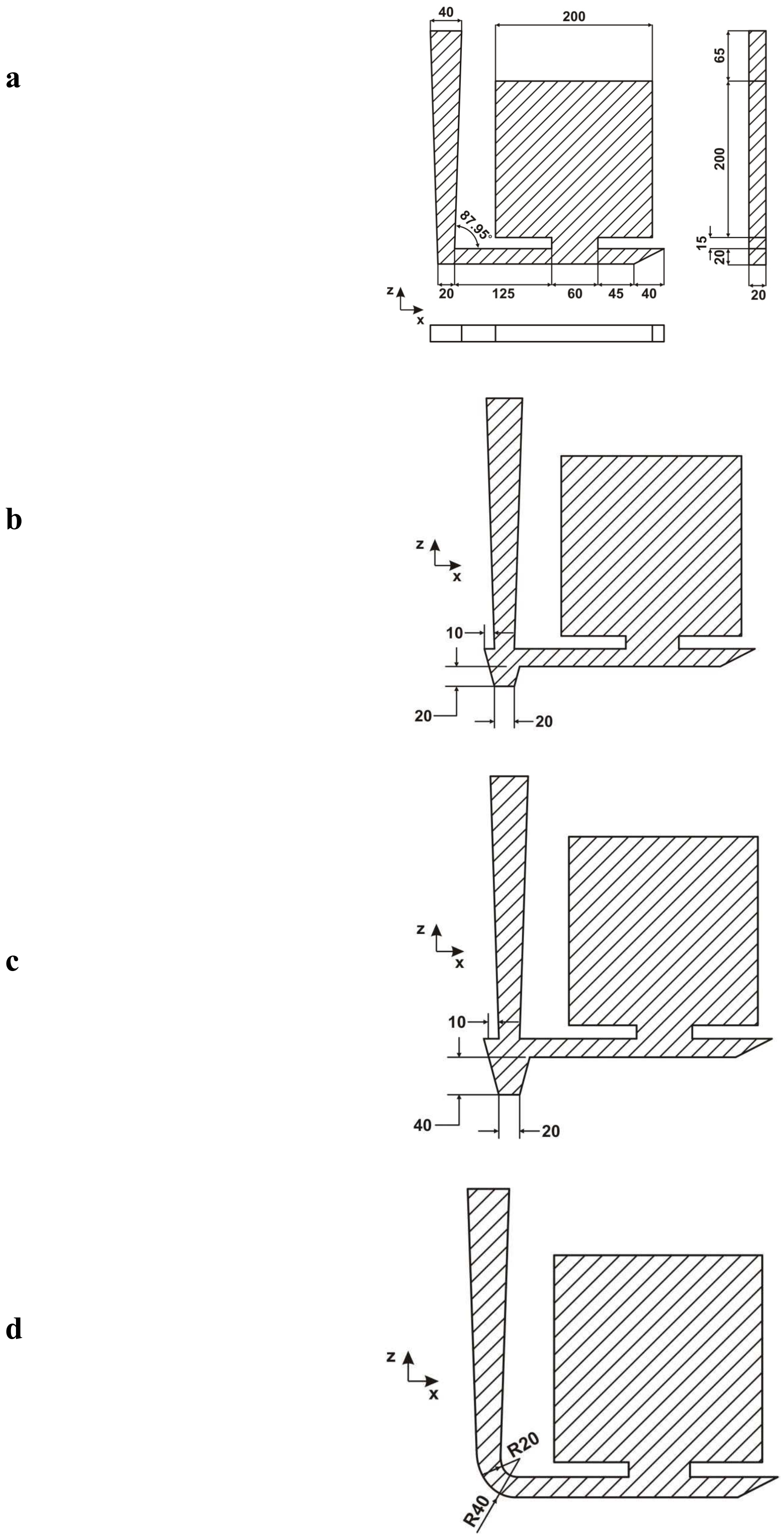

Figure 1

Different designs considered in this study to evaluate the behavior of mold filling with different sprue bases, a- Model A with no sprue well, b- Model B, Standard, c- Model C, Large and d- Model D, Curved sprue base

aluminum alloy (Al-7Si-Mg) castings were obtained by bottom gating a sand mold at an initial gate velocity less than or equal to 0.5 $m.s^{-1}$. The analysis also showed that the bottom gating at a velocity greater than the critical in-gate velocity is equally as likely to produce bad castings as a top gating. It's been also pointed out that a poor running system design promoted formation of large amounts of entrained folded oxide film defects which end to low Weibull moduli in the range 11 to 22 which is as low as ceramic materials. But modifying running system reduced oxides defects with Weibull moduli in the range 38 to 54, which is close to those of aerospace forgings[6]. Campbell[7] has mentioned that if liquid aluminum drops a fairly short distance of 12.5mm, the velocity has already reached its critical in-gate velocity of 0.5m.s^{-1} which could entrapped insoluble films and generates bi-film defects.

Table 1
Initial and boundary conditions

Model	PI[a] (Pa)	FT[b] (sec)	TNCM[c]
A	1172	2.6	111006
B	1172	2.62	115776
C	1172	2.64	123228
D	1172	2.36	109503

[a]Pressure Inlet, [b]Filling Time, [c]Total Number of Cavity Meshes

Due to the importance of mold filling simulation and with aim of achieving a perfect sight of casting, extensive research effort has been made in attempt to study the effect of gating design on the flow pattern of melt entering the mold[8,9]. In one of these studies effect of cross-sectional shapes of runner on mechanical strength of Al-7Si-Mg alloy has investigated by X. Dai[10]. Their numerical and experimental results showed that the Runner with circular cross section is much more effective than that of rectangular and triangular in keeping in-gate velocity under critical velocity, avoiding the generation of the surface turbulence and the consequential entertainment oxide films.

Table 2
The comparison of x-direction velocity (m.s^{-1}) in different designs (models A, B and D) with model C, in different runner positions

Model	Top	Difference (%)	Middle	Difference (%)	Bottom	Difference (%)
A	0	100	2.75	31.93	3.1	-105.3
B	0	100	3.97	1.73	3.27	-116,55
C	0.67	-	4.04	-	1.51	-
D	0.1	55.22	2.5	38.11	1.14	24.5

It has been observed that if the cross section of the runner after the filter be two times larger than that of the runner before the filter, the liquid metal could be in a permanent contact with the mold walls and slightly pressurized by it. In this condition ceramic filter can play a main role in reduction of velocity and the surface turbulence of the liquid metal in naturally pressurized system[11].
Reduction of velocity as a result of converting dynamic pressure to static one could be accomplished by using a diffusing passage (diffuser). A diffusing runner system was proposed by HSU[12] to reduce the velocity of liquid metal under critical velocity (0.5 m.s^{-1} for Aluminum), while the flow rate remained almost unchanged.

Table 3
The comparison of filled fraction of element in different designs (models A, B and D) with model C, in different runner positions

Model	Top	Difference (%)	Middle	Difference (%)	Bottom	Difference (%)
A	0	100	1	0	1	0
B	0	100	1	0	1	0
C	0.99	-	1	-	1	-
D	0.18	81.81	1	0	1	0

A baffle geometry was created within this new diffusing passage which act as an obstacle. After impacting melt front to the baffle geometry, the flow split into two streams and could spread laterally and fills the sideways region of the diffuser instead of going straight. In this condition velocity will reduce while there is no flow separation from the wall of the diffusing runner, avoiding air or oxide entrapments into runner system. In order to investigate gate size effects on flow pattern, three gate dimension of 9×1, 4.5×2 and 6×1.5 (mm^2) were employed in a non-pressurized system for evaluating melt flow in a horizontal plate using direct observation method. It was found that increasing thickness of gate in a constant area will increase pressure head at the gate exit which could increase melt velocity[13]. In-gate velocity is not a main parameter only in gravity casting to be controlled. Venkatesan[14] has found that an increase in gate area will result in a reduction in gate velocity which will result in reduced inertia effects and increase in the tendency toward continuous fill which is a desirable phenomenon in high pressure die casting.

Besides all gating system portions, design of sprue base as a liquid plumbing system into the runner has received much attentions by researchers over the years. When the metal has completed its controlled flow down the sprue, it moves at rather high velocities. Then, to introduce into the runner, it has to change direction and flow at a right angle relative to the sprue causes splashing into the runner system. Again, this exposes large amounts of metal droplets to atmospheric conditions. Webster[15] believed that, by placing a small well at the bottom of the sprue, the molten metal can hit the bottom and lose excessive kinetic energy before entering the remaining portions of the gating system. R. Elliot[1] mentioned that the formation of *vena contracta* could be suppressed using a properly sized well which is able to reduce the surface turbulence.

Schwam[16] has explained two melt flows generated as soon as the basin begins to fill. One closer to the runner which proceeds into the mold and the other half begins to circulate in a "whirlpool" fashion. He analyzed that with the filled basin metal starts to forgo the basin and the flow acts as if no sprue-well is present at all.

As indicated by Campbell[2] after the well was filled, the rotation of the liquid in the well was seen to act as a kind of ball bearing, reducing the friction on the stream at the turn. In this way the velocity in the runner will increased. Moreover, contacting liquid metal with the runner when no well was used had the benefit of additional friction from the wall rather than using a well which caused useful reduction in metal speed.

The objective of this study is to investigate the effects of sprue base on flow pattern of liquid during mold filling using modeling based on computational fluid dynamics (CFD), focusing

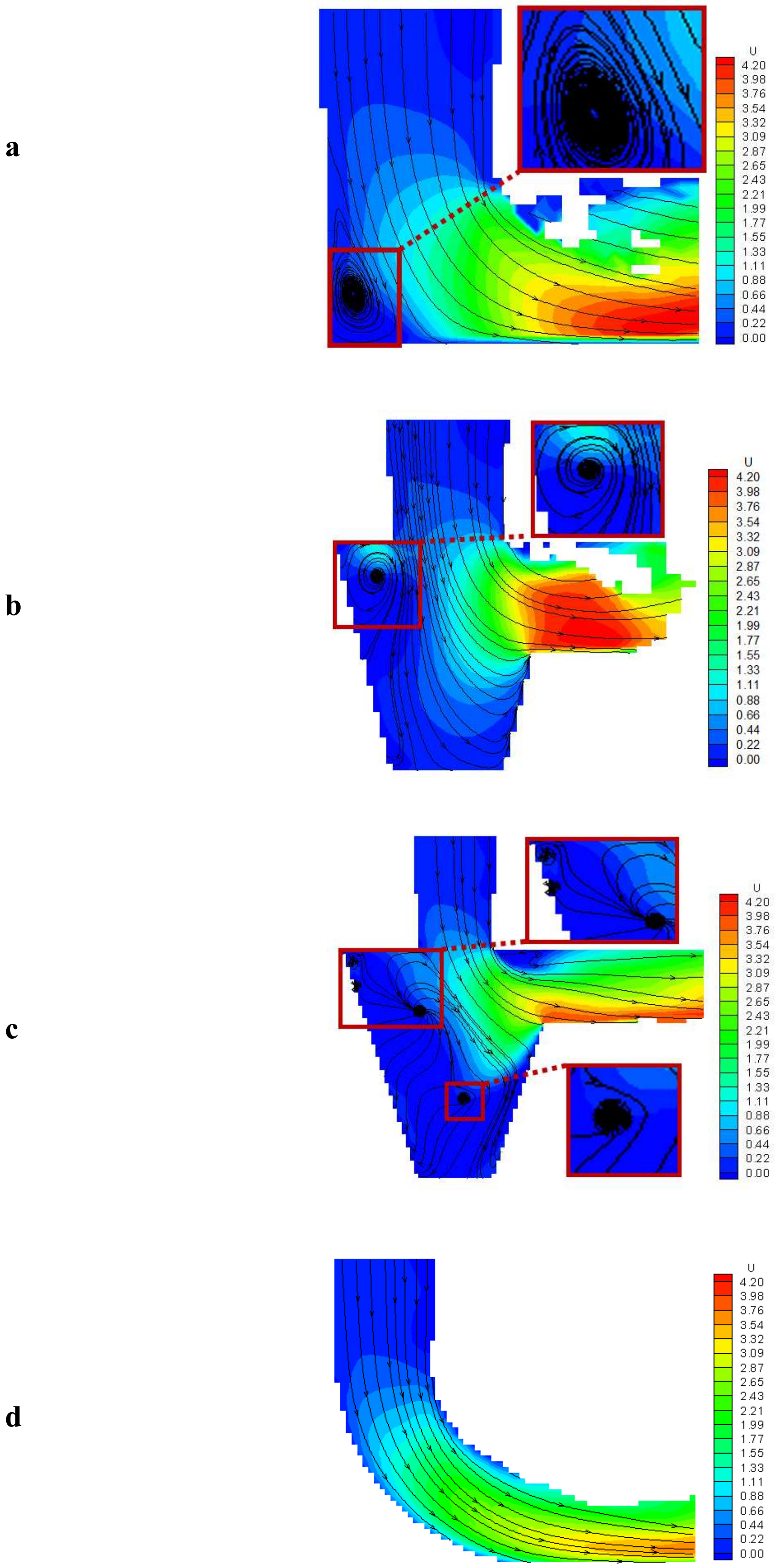

Figure 2
Contours of velocity in the x-direction and streamlines
in a- no sprue well, b- standard, c- large and d- curved sprue base

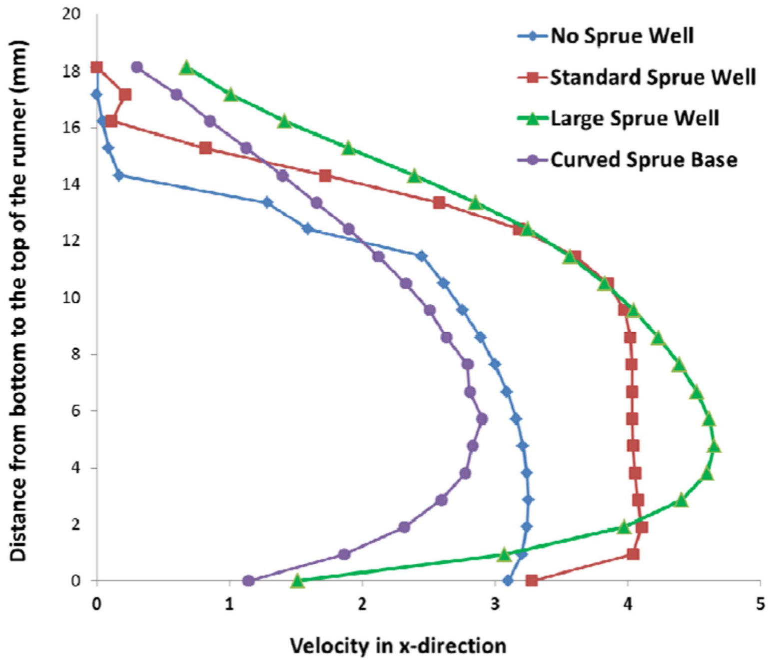

Figure 3
Velocity distribution from top to bottom of the runner

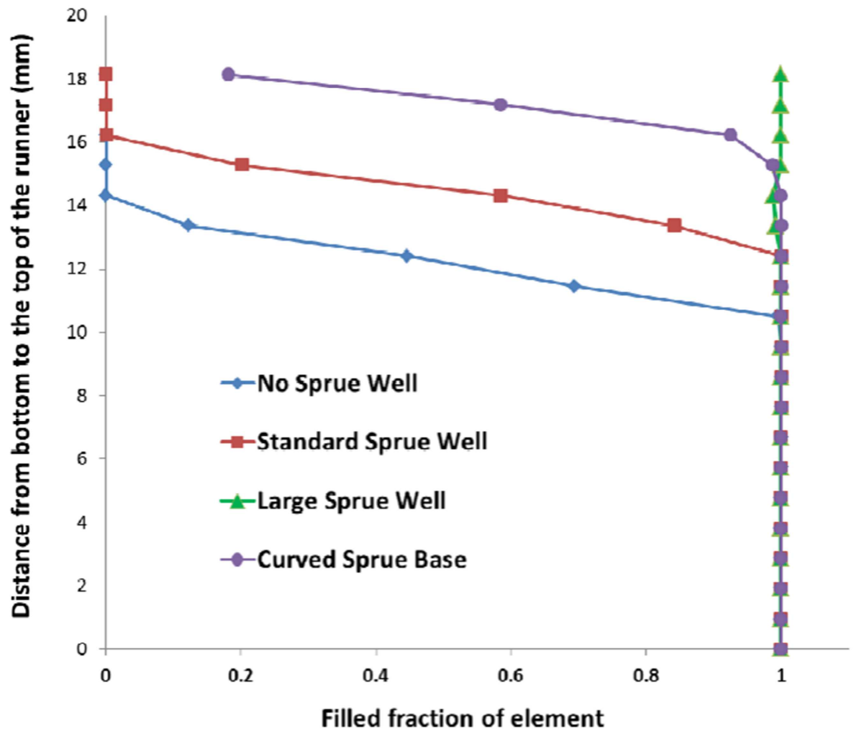

Figure 4
Filled fraction of element with liquid metal

on the relationship among sprue base design, streamlines pattern and runner and in-gate velocity distribution. Three gating systems were designed which the only difference between them was size of the sprue bases and another one was design with a curved sprue base. Streamlines and velocity distributions in different locations were analyzed precisely to evaluate the effect of sprue base on reduction of velocity, Surface turbulence and formation of *vena contracta*.

2. Methods and Procedures

2.1 Model Selection

In order to evaluate different scales of sprue bases, an unpressurized system with different wells considered beneath the sprue. The details of dimension of four shapes has been shown in Fig. 1 including no-well , standard sized, over-sized wells and no-well with a curved sprue base. The dimensions of all molds and gating systems are identical except for sprue bases. Models include a sprue, sprue base, runner, gate and a rectangular casting part. This arrangement, similarity of different molds except of sprue bases, allows for direct comparison of the behavior of liquid metal flow and performance of the castings acquired by using different sprue bases.

2.2 CFD Model

In order to simulate the metal flow in gating systems with different sprue base, CFD modeling was used. This study employed the code SUTCAST. In the filling simulation, the volume of fluid (VOF) method was implemented to track the moving free surface of molten aluminum in the gating system. Non iterative method of SOLA was employed to solve Navier-Stokes equation. Internal boundary condition of no-slip was used to evaluate effect of mold friction on filling behavior. All the mentioned equations were solved on the grids containing cubic mesh. At the curved and tapered boundary conditions cubic mesh couldn't fit the geometry completely and the generated meshes appear like steps. This step like mesh generation in boundary conditions could act as an obstacle against fluid flow, change the direction of melt and cause a back pressure which could have undesirable effects on mold filling. For the purpose of minimizing mesh dependency effects of cubic mesh generation on flow behavior a mesh refinement was carried out intentionally in the region of sprue base to achieve a nearly smooth boundary condition. The summary of the initial and boundary condition are mentioned in table 1.

3. Results and Discussion

3.1 Effect of Sprue-Well on Filling Pattern

In order to evaluate the effects of the geometry of different sprue-wells on filling pattern during mold filling, streamlines at the first time step which liquid metal goes out of the well and enters to the runner were analyzed. Fig. 2 shows streamlines for all sprue-wells which represents the resultant of velocity in x and z directions. With tracing these streamlines in all models, it was observed that in model A with no Sprue-Well, a small vortex flow was generated at the bottom of the sprue base which this vortex flow was increased with increasing well size while in model D with a curved sprue base, no vortex flow was observed. The rotation of liquid metals at these points could act as a ball-bearing and pushes the metal into the runner with higher speed. Contours in Fig. 2 show velocity distribution in x- direction which reaches its maximum value right after the well. Maximum velocity behind the melt front increased when the sprue size increased means from 2.9 $m.s^{-1}$ in model D, curved base, to 4.65 $m.s^{-1}$ in model C, largest one (Fig. 3).

3.2 Effect of Sprue-Well on the *Vena Contracta* Formation

The *vena contracta* is a widely observed phenomenon in flowing liquids. It occurs wherever a rapid flow is caused to turn through a sharp change of direction. The base of the down-runner

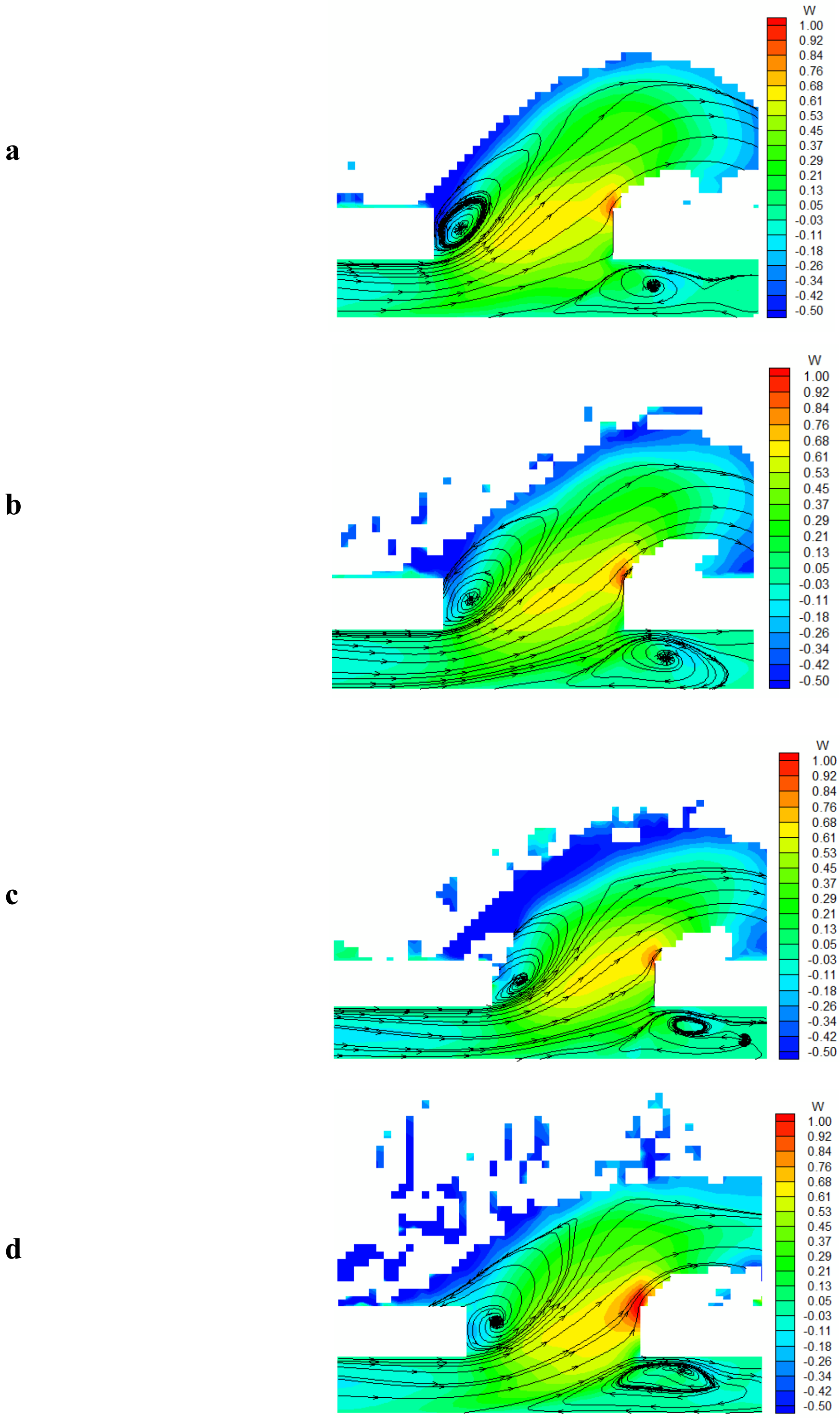

Figure 5
Contours of velocity in z-direction and streamlines in
a- no sprue well, b- standard, c- large and d curved sprue base

is probably an even more important example if, as is usually the case, speeds are much higher here. The loss of contact of the stream from the top of the runner immediately after the turn has been shown to be the source of much air entrainment in the metal. This is expected to be particularly severe for sand molds, where the permeability will allow a good supply of air to the region of reduced pressure[2]. In order to investigate the contact between liquid metal and runner walls an attempt was made to predict velocity distribution in runner right after sprue bases. Fig. 3 shows variation of velocity in x-direction versus distance from bottom to top of the runner after sprue base.

In model A which no well was used and model B with a standard well, velocity increases gradually with increasing distance from top to bottom of the runner. It is concluded that the contact of liquid metal at bottom of runner is much stronger than top and it will increase the probability of formation of low pressure zones. From another point of view, the behavior of velocity changes with changing the well size. In contrast to the model A the velocity reaches its maximum value in more heights in the model C which own the biggest well. In model D with a curved sprue base similar to model C the velocity in runner direction reaches its maximum value at the middle of runner and it depicted that these two types of the sprue base could establish a good contact with runner wall and avoids *vena contracta* formation. However it could be observed that the average and gradient of velocity in model C is higher than that of in model D. It could also lead the casting to higher qualities.

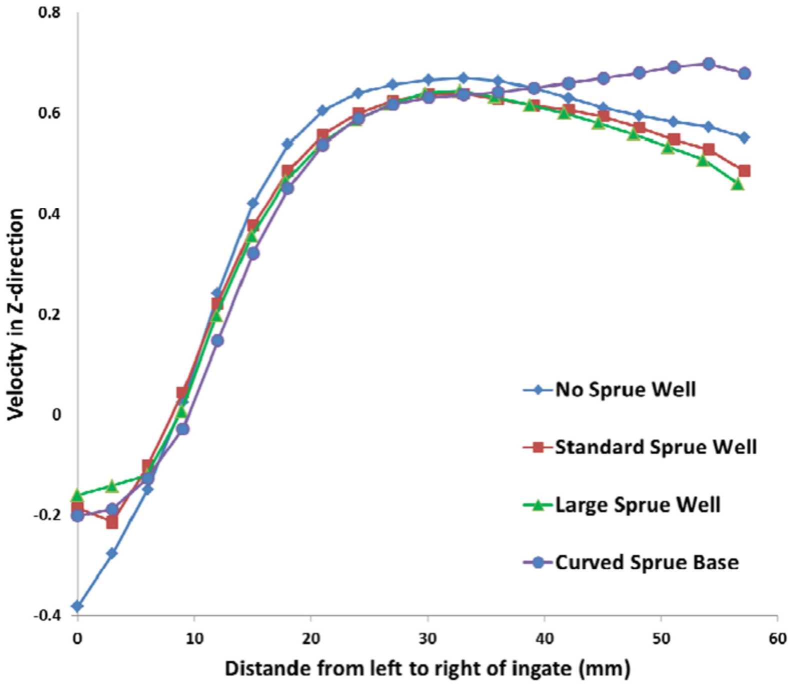

Figure 6
Velocity distribution in z-direction from left side of in-gate to the right side at the middle of in-gate

In table 2, velocity in x-direction after sprue well in different positions is compared for all models. Velocity at top of the runner in model C, with an over-sized well, is much greater than other models especially model A and B. It is demonstrated that the probability of formation of low pressure zone in gating systems where no well were used (model A) would increase dramatically. But velocity concentration at bottom of the runner in model A and B is noticeably higher than model C. The negative difference of velocity at bottom of the runner (-105.3%) confirms that liquid metal in the case where no well where used has a complete contact with the bottom of the runner while formation of *vena contracta* at the top the runner is inevitable.
The fraction of element which is filled with the liquid at the runner entrance is illustrated for different sprue base designs in Fig. 4 where filled fraction equal to one means that element is fully occupied with liquid and the zero value present an empty element. In models A and B it was found that at the top of the runner there are some empty spaces which contain no or small amount of liquid. Moving from top to bottom of the runner the fraction of liquid in elements was increased and reached the value of one. For model D with a curved sprue base, the fraction of liquid at the first 2mm of the top of runner is smaller than one. But for the model C with over-sized well it has the value of one for filled fraction at the top of the runner. This shows that although both model C and D made a good contact with the runner wall but the most perfect contact with the runner wall is belong

to the model C with an over-sized well.
In table 3 the comparison of filled fraction of element with liquid metal in different positions of runner is presented for different models of sprue bases. It is easy to understand that with increasing distance from top of the runner to the bottom the volume fraction of elements which are occupied with liquid increase for the model A where no well where used and model B which employed a standard sprue well. The maximum filled fraction of element at the top of the runner for the model D, using curved sprue base, is 0.18 and increase to the 1 when we move down only 2mm from top of the runner. This show that after model C which fill the runner and make a good contact with runner wall, model D also could be a good alternative for removing *vena contracta*.

3.3 Effect of Sprue-Base on In-gate Velocity

The sizing of the gates should be provided with sufficient area to reduce the velocity of the melt below the critical value of 0.5 $m.s^{-1}$ to keep avoiding formation of surface turbulence and hence entrainment of oxide films. In order to evaluate how sprue well could have an effect on in-gate velocity, distribution of velocity in z-direction at the first time when liquid metal fills the gate and enters the cavity was analyzed (Fig. 5). The velocity distribution in all cases is nearly similar. Maximum velocity (0.7 $m.s^{-1}$) was seen at the right corner of in-gate end which exceeded critical velocity. Vortex flow was observed in the left side of the in-gate. Rotation of liquid here pushes the molten metal back into the runner means negative velocities at this region. As some part of in-gate is occupied by vortex flow, effective in-gate area reduces causes the velocity increases and exceeds the critical velocity.
Velocity in z-direction at the middle of in-gate is depicted in Fig. 6. Here negative values at the left side of the in-gate imply that no molten metal is eligible to pass through this region to the mold cavity. A steep increase in velocity was observed while moving towards right side of the in-gate but it became constant after 20 mm distance from the left side. The maximum velocity in z direction was about 0.7 $m.s^{-1}$ which exceeded from critical value. About 60 percent of gate area remained at this higher velocity while the rest experienced a lower one. It is clear that here the effective area is obviously smaller than that of expected lead to exceeds critical in-gate velocity and splashing of melt into the mold cavity. It could be concluded that in this case with this specific geometry although the velocity in runner is affected by well size but the in-gate velocity is more influence by other casting considerations such as in-gate geometry and location.

4. Conclusion

Effects of employing different sprue bases (No well, standard, large wells and curved sprue base) have been investigated by computational fluid dynamics (CFD) in the present work. Following results were concluded:
1. It was found that locating sprue well in gating system especially larger ones; increase the possibility of formation of vortex flow in sprue base which cause increase in surface turbulence and therefore entrainment defects.
2. Rather large wells could eliminate *vena contracta* while keeping a full contact between the runner wall and liquid metal.
3. Curved sprue base produced no vortex flow at the bottom of sprue with a nearly full contact between the runner wall and liquid metal. Liquid metal has experienced the lowest velocity at the runner in this design.
4. In-gate velocity was observed nearly the same for all sprue base systems. It was demonstrated that in-gate velocity depends on other casting considerations such as distance between sprue and gates, gating system geometry and ratio.

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