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THE DESIGN OF L-SHAPED RUNNERS FOR GRAVITY CASTING

Fu-Yuan Hsu[1], Mark R. Jolly[2] and John Campbell[2]

[1]Auspicium Co., Ltd., 2F-3, No.4, Sec.1, Jen-Ai Road, Taipei, Taiwan, R.O.C.
[2]University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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Abstract

The purpose of this research is the development of guiding principles and rules for the design of filling systems for aluminium gravity castings. The approach employs computational modeling and real-time X-ray radiography. Out of five geometries of L-junctions that occur in filling systems and which have been studied, space dictates that only the sprue/runner junction is presented. Progressive filling along the L shaped geometry has been achieved without surface turbulence by eliminating excess cross sectional area of the channels, and in particular reducing the “dead zone” in the corner of the junction. Higher flow rate and less turbulent filling of the mould cavity can be achieved by the new L shaped junction design.

Introduction

Rules for designing the pouring basin and sprue were well established in previous works [1, 2] leaving this research to focus on the development of guidelines for the design of the next feature of the running system, the sprue/runner junction.

The requirements for a good running system can be summarized as the prevention of the entrainment defects into the casting in the early stage of mould filling [2-4]. The liquid metal should fill progressively along the running system without developing surface turbulence that would risk the entrapment of defects such as bubbles and bifilms into castings.

However, at the base of the sprue, the high velocity of the liquid metal is inevitable, well above the critical velocity [5] introducing the significant risk of entrainment problems. To avoid the formation of defects, the design of the L-shaped junction, between the vertical runner (the sprue) and the horizontal runner, becomes a critical task. This junction does not appear to be well understood in terms of fluid dynamics; hence the reason for this study.

Method

Computational modeling

A computational fluid dynamics (CFD) code, Flow-3D™ [6], has been used for these studies. Flow-3D™ is based on the finite-volume-method, which is originally developed as a special finite difference formulation. Since the flow phenomena in running systems were mainly considered here, one fluid (i.e. liquid metal) with sharp interface tracking using the volume of fluid (VOF) algorithm was employed in the modeling. The sand mold was assumed to have a high permeability, so that the generation of back-pressure from air and/or gas in the cavity during filling was ignored. Empty cells within a domain were therefore present as voids at no pressure, equivalent to the assumption that atmosphere pressure exists throughout the filling process. Isothermal conditions were assumed allowing any change of viscosity of the liquid to be ignored as approximately only 1 per cent of heat loss was expected (c.f., Richins and Wetmore [7]).

The simulations were carried out on a Silicon Graphics Octane (R10000-IP30) machine, running a 175 MHz CPU and 640 MB memory. The operating system was IRIX version 6.5 (Silicon Graphics). The input parameters, which were selected for the modeling of liquid alloy Al-7Si-0.4Mg in the options of Flow-3D™, have been listed previously [8, 9].

L shaped junctions in 2-dimensions

The 2-D condition is a theoretical approximation to reality that has the benefit of simplicity. It may be considered when the flow in the third direction is non-existent and when the effect of friction forces resulting from the boundary walls in that direction can be ignored.

A series of 2-dimensional geometries were constructed having one-directional flow with a uniform velocity impacted into the right angle of different L-shaped junctions. The geometry of flow issuing from the junction depended on the space available. Effectively, the approach constrains one side of the flow stream and measures the profile of the other free side in a 2-dimensional condition. With sufficient space the unconstrained flow profile in this L-junction could be characterized by a number of measurements, but in this report limitations of space dictates a focus on only one dimension, probably that of greatest interest to the casting engineer: the inner radius R_i. Fitting an appropriate inner-radius R_i to the curve of the transition flow, a three-point method was used that involved a potential error of about ± 2.5 mm.

The computational approach for 2D an L-shape junction

Figure 1 presents a schematic illustration of an L-shape junction. The basic variables, the "Inlet-opening I_o" and "inlet-velocity V_i" were systematically studied to characterize their influence on the design of the junction.

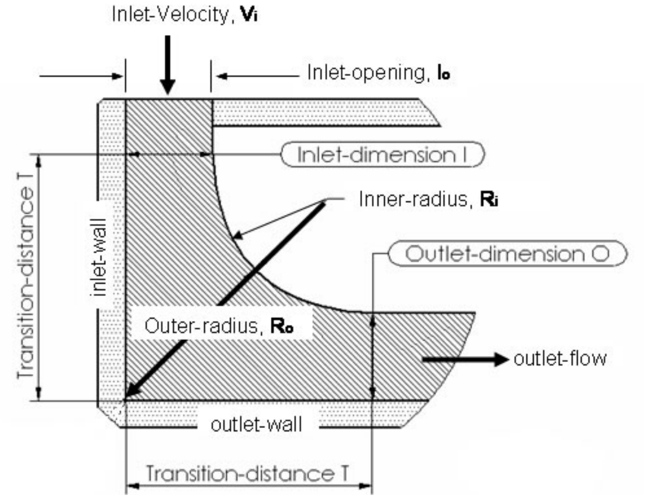

Figure 1 schematic of a L-junction and the profile of transition flow determined by the five dimensions (i.e., I, O, R_i, R_o, and T)

All the outputs have been reported in terms of the "Inlet-opening I_o". In the 2-dimension case, the Inlet-opening I_o can, of course, be simply characterized by a length. The variables geometrical assumptions were

1. Various inlet-opening I_o (1, 4, 8, 12, 16, 20, 24, 28, and 32 mm for L-shape wall) were built.

2. Various unidirectional inlet-velocities V_i (1, 2, 4, and 8 $m \cdot s^{-1}$) were applied as initial boundary conditions.

Figure 2 demonstrates an example of the 2D simulation with the inlet-velocity $Vi = 2.0\ m \cdot s^{-1}$ and inlet-opening $I_o = 28$ mm (L-shape junction V_i2I_o28) at various time frames.

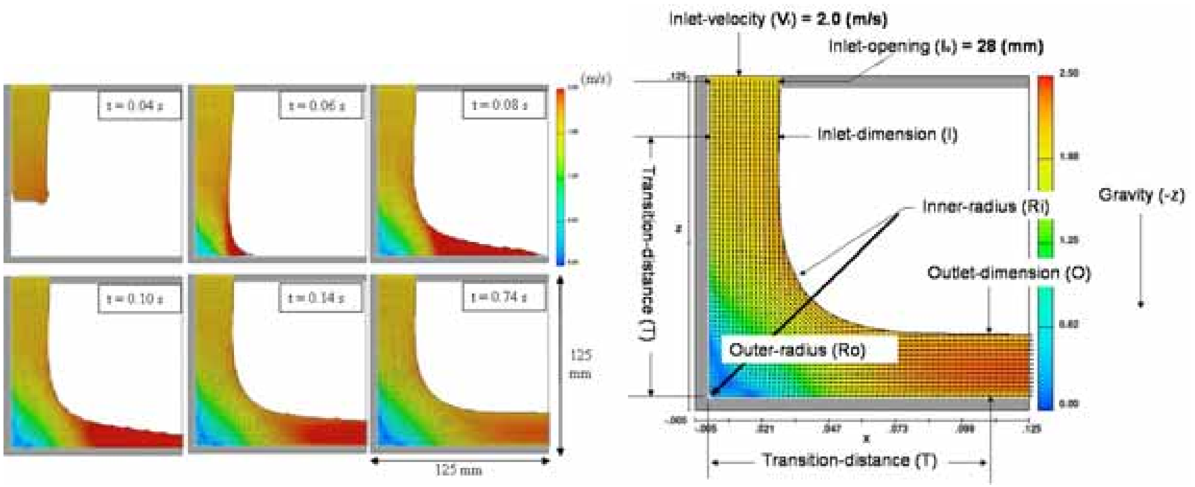

Figure 2 a series of frames for the 2-D modelling result of the L-shape junction V_i2I_o28.

L shaped junctions in 3-dimensions

To explore the appropriateness and validity of the 2-D design a 3-dimensional computational model was constructed (Figure 3(a)). Because of the velocity boundary condition of uniform one-direction flow entering the top of the domain, the geometry of the hyperbolically tapered sprue was constructed assuming conservation of mass. An entrance velocity into the sprue of 0.891 $m \cdot s^{-1}$, equivalent to a head height of 40 mm in the pouring basin, was assumed. Thereafter, a 260 mm height of hyperbolic shape of sprue was designed, giving a total head height of 300 mm.

A Radius-Bend geometry (Figure 3(b)) was modeled to compare with the former sharp L-junction. An appropriate geometrical profile of the channel is not known a priori. Thus an outer-radius, tangential to the inlet-wall and the outlet-wall, was constructed assuming the depth in the middle of the bend corresponded approximately to the average of the inlet- and outlet-dimensions of the flow in the original right angle L-shape.

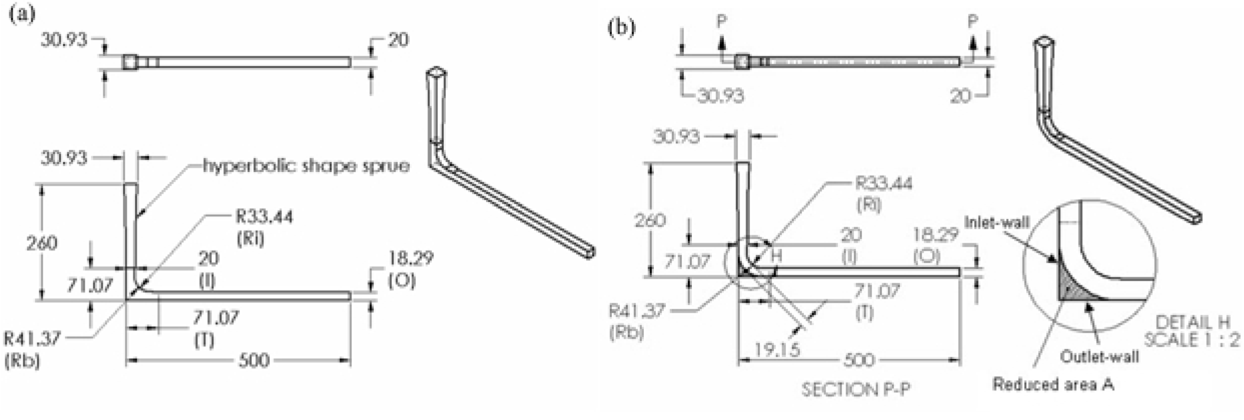

Figure 1 The 3-dimensional (a) “L-shape” and (b) “Radius Bend” of the sprue-runner junction.

Video X-ray radiography study

The main role of the real-time X-ray radiography was to verify the results of computational modeling. A ‘real’ casting incorporating the sprue-runner junction was investigated using a square sprue of total head height 300 mm. The technique has been described previously [9]. Radiographic images do not reproduce clearly, and so are not presented here. Radiographic results are available on request from the corresponding author.

Results

L shaped junctions in 2-dimensions.

The effect of various inlet-velocities V_i on the profile of flow for the L-shape junction are plotted in Figure 4. The dimensions of the outer-radius R_o, inner-radius R_i, and outlet-dimension O are normalized by inlet-dimension I.

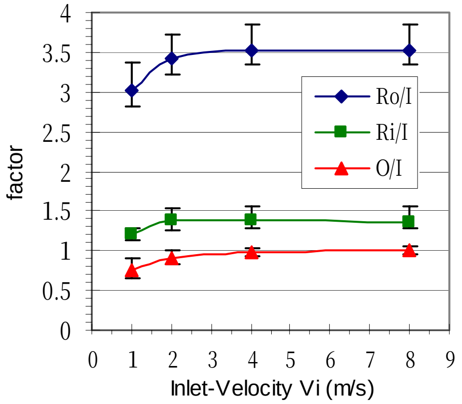

Figure 4 In the 2-D L-shape junction, the ratio of the dimensions, which are the outer-radius R_o, the inner-radius R_i, outlet-dimension O, over the inlet-dimension I, against to various inlet-velocity V_i.

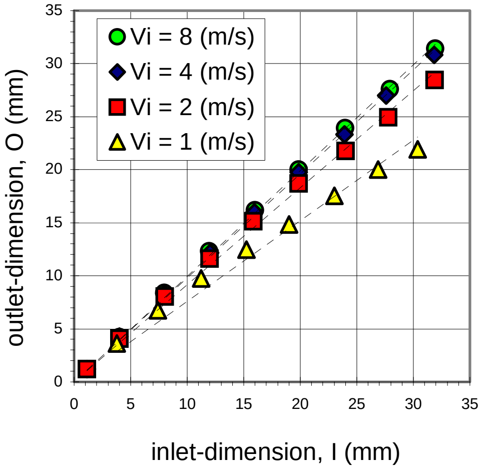

Figure 5 The outlet-dimension O versus to the inlet-dimension I for the 2-D L-shape junction with various inlet-velocity V_i.

L shaped junctions in 3-dimensions

Three experiments for sprue-runner junction designs are investigated in this section. They were a 3-D L-shape simulation, a 3-D Radius-Bend simulation, and an L-shape in real casting.

3-D L-Shape Simulation

The simulation results of the L-shape in the center plane are shown in Figure 6(a). Before the time frame of 0.13s, the liquid metal filled completely the hyperbolic square sprue. Also, the flow front advanced progressively without leaving any empty region in its wake. At 0.13s, the liquid metal starts to fill the L-shape of the sprue-runner junction. The magnitude of velocity at that time was 2.27 m·s^{-1}. At 0.15s, the flow impacted on the base of the runner. At 0.24s, the flow filled the L-shape completely. At 0.31s, the running system was completely filled and the maximum velocity of the flow at the exit of the runner was 2.56 m·s^{-1}.

3-D Radius Bend Simulation

Figure 6(b) shows the results of the radius bend in the center plane. Again, before 0.13s, the flow gradually filled the square-sprue down its hyperbolic shape. At 0.13s, the flow began to fill the sprue-runner junction of the Bend-shape. The velocity was 2.22 m·s^{-1}at that time. After 0.13s, the flow filled the outer side of the Bend-shape and the base of the runner. The flow moved toward the inner side of the Bend-shape progressively without creating empty regions. At 0.18s, the bend was completely filled. At 0.31s, the whole running system was filled and the maximum velocity of the flow at the exit of the Bend-shape runner was 2.65 m·s^{-1}.

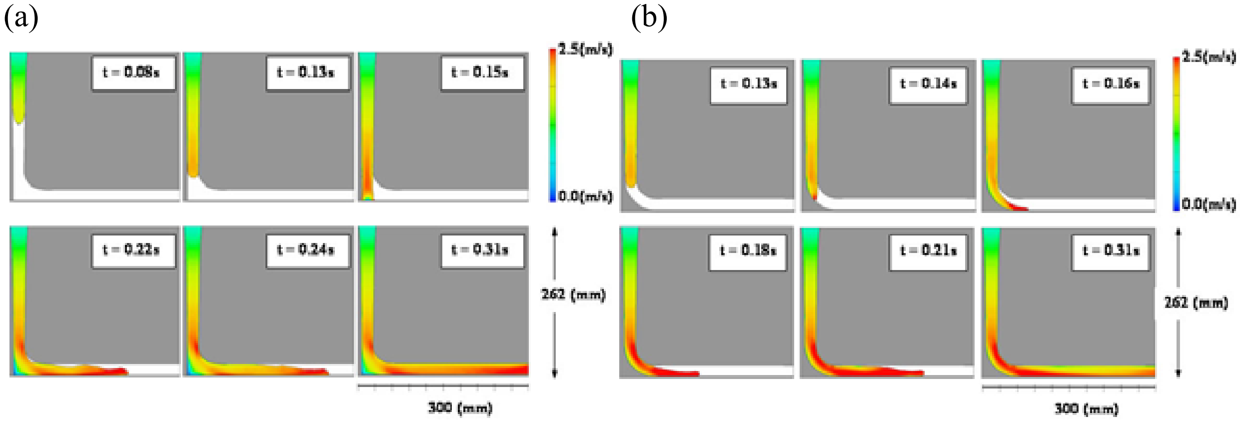

Figure 6 The modeling result of (a) the 3-D L-shape and (b) the 3-D Radius-Bend shape on the centre plane.

L-shape in real casting

At the time frame of 0.16s, the flow entered the L-shape junction. At 0.20s, the flow impacted on the base of the junction. At 0.24s, the flow direction changed from vertical to horizontal direction. At 0.28s, the junction was completely filled. The velocity at the end of the runner was measured by the trajectory method in which the melt was observed to create a free-fall parabola shape during which was captured by video and measured (air resistance to the trajectory was neglected). The velocity of the flow was highest, 2.23 m·s^{-1}, at 0.08s. After this peak velocity, the flow settled to a constant velocity of 1.69 m·s^{-1} from 0.4s to 3.16s, after which it declined until the end of flow at 4.5s. Due to parallax and other errors, the total potential error of measurement could be 2.63 mm corresponding to a potential velocity error 0.11 m·s^{-1}.

Discussion

L shaped junctions in 2-D

The following discussion will be based on the example of L-shape junction (Figure 2), which has inlet-opening I_o = 28 mm and inlet-velocity V_i = 2 m·s^{-1}. In Figure 5 the outlet-dimension versus the inlet-dimension is plotted. It shows that the inlet and outlet dimensions tend to become identical as the inlet-velocity approaches 8 m·s^{-1} implying that the influence of gravity reduces at high velocity.

In the exercise described in this work, only the walls on the outside of the bend constrain the flow, whilst the inner side of the flow remains open to the free space of the runner. However, by tailoring a channel to the exact predicted shape of the junction so that the channel walls would contain the flow completely, confining the flow by walls on all sides raises the issue that the additional wall naturally provides friction, locally reducing its velocity. However, of course, the velocity profile of the flow will change relatively little since the majority of the flow will be concentrated in the centre of the runner. The additional, relatively small, influence of friction will act to assist the channel to remain fully filled by a slight overcompensation, conferring a reassuring factor of safety for the complete filling of the channel.

Even so, the 2D model is probably too oversimplified to be helpful in the design of real 3D systems mainly because as it stands only the outer surfaces contribute to frictional drag. This minimal drag is corroborated by the inlet and outlet velocities being nearly equal. For the 3D model the area of surfaces contributing to frictional drag is four times greater.

Junctions in 3-D

Simulated L-shape and Radius Bend in modeling

In the modeling of the L-shape of sprue-runner junction, the flow enters the geometry at 0.13s. At 0.24s, this geometry is completely filled. Thus, the duration of filling this geometry, the "clean-up" time, is 0.11s. For the Bend-shape, the "clean up" time can be taken to be merely 0.05s, being the time from 0.13s to 0.18s taken for the flow to travel around the bend. This shorter time corresponds to the reduced volume of the junction by the removal of the 'dead zone' in the corner of the junction. It is seen therefore that the Radius Bend approach is not only economical but has an improved flow behavior.

Considering the 'clean up' period more strictly, since no entrainment or air or surface appear to occur at any time, this time can be said to be zero for both of these junctions. Even if not considered zero, these times are far less than those required in the traditional sprue-runner junction designs by Grube *et al* [10], in which their optimum 'clean-up' times are from 1 to 3 seconds.

L-shape in a real casting

In the filling of the real casting observed by video X-ray radiography, it is clear that there are some empty regions in the base of the L-shape junction. These empty regions are probably the result of the rather 'ragged' fall of the melt down the sprue for the first fractions of a second. After the flow impacts on the floor of the system the flow is deflected as a jet toward the exit of the runner. As a free stream emerges from the end of the runner, contact with the walls is minimal, so that frictional resistance is negligible. In the results of the real L-shape casting experiment the exit velocity from the junction at the beginning of the flow was 2.23 $m \cdot s^{-1}$; quite close to the theoretical velocity 2.43 $m \cdot s^{-1}$ for a free fall from 300 mm, confirming that the jet does not totally contact the surfaces of the walls of the running system in the early phase of the filling.

The high-speed jet began to slow down as the flow completely filled the whole system. The "clear-up" time of the L-shape junction is 0.12s (from the beginning of entering at 0.16s to the fully filled condition at 0.28s). The velocity measured by the trajectory experiment at this stage was 1.69 ± 0.11 $m \cdot s^{-1}$; a 30% reduction in the speed at the sprue base. In Table 1 the head losses on each part of the real casting and the loss coefficient of the L-shape junction were estimated. It shows that the head loss of the L-shape junction (0.016m) is a minor loss in comparison to the major loss of sprue (0.082m). And, in the calculation, the loss coefficient, K_L, of the L-shape junction is 0.110. The detail calculation was shown elsewhere [8].

Generally, the modeling appeared to give substantially similar profiles of the flow to the real casting at the various stages. However, some details of the flow appear different as discussed below.

The filling time in the model is always less than that in the real casting. This feature was also found in the benchmark test 1995 of Flow-3D modeling. In an attempt to counter this Barkhudarov and Hirt [11] used an effective viscosity 5 times higher than the molecular viscosity of pure aluminium to prolong the filling time from the original modeling prediction of 1.5s to the experimental time of 2.2s. In this work also the original molecular viscosity was employed, corroborating once again shorter predicted filling times. The assumptions of isothermal and one-fluid (i.e. no air) are thought to have negligible influence on this problem. It seems more likely that bifilm defects in suspension in the melt are likely to significantly increase the effective viscosity; a factor of 5 does not seem unreasonable for typical concentrations of bifilms. (High concentrations of bifilms can increase the viscosity by a factor of 10^3 or more, and are not uncommonly seen as melts of porridge-like consistency). In addition, the presence of the oxide film on the advancing meniscus, having to be continuously broken (but of course continuously re-forming) as a result of its being dragged back against the walls of the channels, is likely to contribute a real and observable drag on the melt.

Table 1 head and head losses for each parts in the real casting of the L-shape junction.

Parts		Head height (m)	Loss coefficient, K or friction factor, f	Source of coefficients	Others data for calculations
Head losses	Sprue entrance	0.014	$K_E = 0.30$	Richins and Wetmore[7]	VE = 0.95 m·s^{-1}
	Sprue	0.082	$K_S = 0.563$	Srinivasan [12]	$\overline{V}_2 = 1.69$ m·s^{-1}
	L-shape junction	0.016	$K_L = 0.110$	Present author calculated	$\overline{V}_2 = 1.69$ m·s^{-1}
	Runner	0.032	$f_R = 0.04$	Richins and Wetmore [7]	$\overline{V}_2 = 1.69$ m·s^{-1} $l_R = 0.070$ m $D_R = 0.01277$ m
Velocity head at exit of the runner		0.156	The kinetic energy coefficient, α = 1.07	Present author estimated (c.f., Fox and McDonald [13])	$\overline{V}_2 = 1.69$ m·s^{-1} (Trajectory method)
Total head height		0.300			

The breaking away of the flow from the surface of the channel contrasts with the modeling that indicates that the flow is always against the surface of the wall. The relatively coarse mesh selected for the simulation to reduce the computation to reasonable times of the order of 48 hours may have contributed somewhat to this small deviation from realism. However, the major contributor in practice is more likely to reside with the experiment rather than the simulation as a result of the imperfect initial priming of the sprue in real casting conditions.

Conclusions

1. Guidelines for the designing of L-junctions have been developed.

2. The 2D models are relatively poor simulations compared to the 3D models of junctions.

3. Progressive filling along the L-junction geometry can be improved by reducing the area of the "dead zone".

4. L-Junctions, if designed as in this study, have a relatively small frictional loss compared to the longer length channels of the filling system such as the sprue and the runner.

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