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Flow Rates in Multi-Gate Systems: Experimental and Simulation Studies

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Abstract

Mold filling takes the shortest time in the lifecycle of a cast product, yet exerts the most influence on its quality. Complete, smooth and uniform filling of mold with clean metal is achieved by an appropriate gating system, which comprises one or more pouring basins, sprues, runners and gates. The number, location, shape and size of the gating elements determine the sequence and rate of flow of molten metal into the mold cavity. There are however, no mathematical models to estimate the discharge and volume of flow through each gate. This is needed to balance the flow through multiple gates (by adjusting their position and cross-sectional area), and to ensure that the mold cavity is filled in an optimal time. In this work, we present experimental and simulation studies on discharge through multiple gates connected to a horizontal runner. Experiments are conducted by tap and collect method using water and the volume of flow through each gate is observed for two different set ups: end-sprue and centre-sprue. The results are compared with computer simulation, providing valuable insights useful for designing multi-gate systems.

Keywords: Gating system, hydraulic approach, numerical simulation.

1. Introduction

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. In this paper, we first review hydraulic based analysis of gating systems. Experiments on a multi-gate gating system using water in a transparent mould are performed to study the flow behavior. Later commercial software is used to simulate the experimental models.

Proper design of a gating system can be made easier by the application of several fundamental principles of fluid flow. Chief among these principles are Bernoulli’s theorem, the law of continuity, and the effect of momentum. 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.

One of the earliest investigation of flow through gates was published by Dietert *et.al.,* (1926), who from practical experience established a law for pouring rate, depending on the thickness of section cast and casting weight which was later used to find the total ingate area using an empirical formula. Later many researchers developed different empirical relations either based on Dietert’s equations or their own for gating system design. Petin (1937, 1939) modified Torricelli’s formula to also incorporate the height of the casting, for top and bottom pouring, from which he calculated the overall loss-coefficient. Several investigators, Osann (1939), Lehmann (1941), Stone (1951) used modifications or similar formulas to compute the total ingate area and loss-coefficients. These empirical relations were later proved to be limited to a particular casting. This influenced many researchers to apply hydraulic principles to design gating system in castings.

Most of the investigations mentioned above aimed at calculating the total ingate area required to fill a casting in a given time. Through experimental investigation, it is well known that in the case of castings fed through several gates, all the gates do not fill evenly and some of them carry more molten metal than others. Johnson *et al.,* (1950) observed that the discharge is highest in the gates farther to sprue and it reduces from farther to nearer gates. It is possible from hydraulic principles to calculate the amount of metal carried into the mold by each ingate at least for the case where gates are on the same level. The first analysis of overall loss coefficient on a hydraulic basis was carried out by Miaskowski (1932). He considered gating system composed of an assembly of geometrically simple components and worked out the total friction losses as a sum of individual losses at these various components. He derived equations for loss-factors, determined by the flow of water.

A comprehensive theoretical and experimental study was carried out by Berger and Locke (1951) in the context of applying fluid dynamics in design of multiple-gating systems by making use of continuity equation, Bernoulli’s equation of law of conservation, and discharge equation. He suggested that the ratio of flow rates from two gates depends on the two dimensionless ratios (gate to runner area ratios and discharge coefficient ratios). It implies that flow ratios are apparently independent of the distance between the gates, or the length of the runner between the gates.

Ruddle (1955), proposed a method for calculating relative flows from different gates by precisely computing the frictional and head losses at different channels. The total losses represented by the coefficients, are the sum of several separate losses. This enables the overall losses to be computed, provided the individual coefficients are known.

The pipe-node-path representation proposed by Kannan (1991) and later modified by Bradley et al., (1993), facilitates data input and automatic assembly of the system of energy balance and continuity equations governing flow in the gating system. The approach is to represent a gating system as an assembly of pipe segments connected at nodes. Individual pipe segments are identified with numbers and nodes by alphabets. Determination of the flow rate in each pipe segment is accomplished by writing an energy balance equation for each path in the system and a continuity equation for each node, and then by solving the system of simultaneous algebraic equations.

Large castings require multiple gates so that all sections fill at approximately the same time. Uniform filling ensures less variation in mechanical properties developed during solidification. This is influenced by flow parameters like pressure, velocity, discharge and geometric parameters in a multi-gate gating system (Figure 1). Discharge variation in such a system reported earlier (Johnson et.al, Berger et.al) shows only a discharge trend in a multi-gate system.

Actual discharge in each gate is required to optimize the flow to be smooth and uniform. To determine the correct location and cross sectional area of each gate in such a gating system, discharge through each gate has to be predicted. This requires the determination of loss coefficients during flow through the gating channels. The current work presents the results of experiments carried out on horizontal multi-gate gating system with four gates, followed by computer simulation, to study the variation in discharge and velocity. The experimental setup and observations are discussed in the next section.

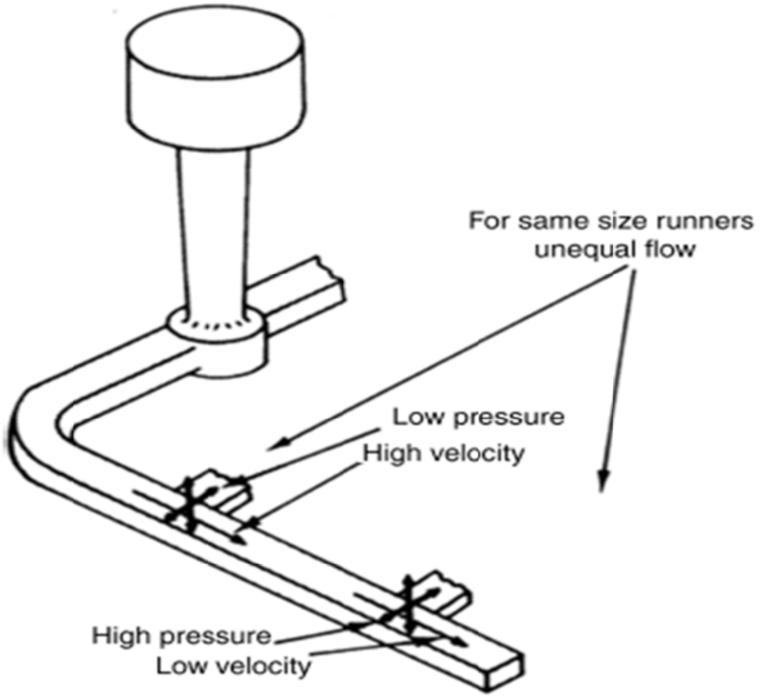


Figure 1: Flow through multiple gates [ASM, 2009]

2. Experimental Studies

The modular experimental setup for studying the flow of liquid in a multi-gate gating system is shown in Figure 2. It consists of a pouring basin, a tapered sprue of circular cross section, a runner of constant square cross section (15 mm x 15 mm) and four gates of same area of rectangular cross section (9 mm x 18 mm). All these are cut into Perspex blocks and joined for leak-less flow of water. The experimental setup is designed with a gating ratio of 1: 2: 1.5. In the first set of experiments, the sprue is placed at one end, with all four gates to one side, spaced equi-distant from each other. In the second set of experiments, the sprue is placed in the centre, with two gates on either side as shown in Figure 3. Each set includes seven experiments, with different combinations of gates being open or closed. Water is pumped into the pouring basin to maintain a constant head. Potassium permanganate is used to colour the water for better visibility during its flow. The amount of water coming out of each gate is collected into jars and measured. The total time, from start of filling of pouring basin to 2000 cm^3 volume of flow through the pouring basin, is noted. Each individual experiment is repeated thrice and the average values are used for analysis. All experiments are also recorded on video for verification and analysis.

The observations of the experiments are tabulated in Table 1 for end sprue arrangement and in Table 2 for centre sprue arrangement. In the end-sprue arrangement, the time taken to fill a given total volume of liquid depends on the number of open gates and their position, as seen in Table 1. In the first experiment, all four gates are open and fill time is just under 10 seconds. In the last two experiments only one gate is open, and the fill time is more than 12 seconds. However, in experiment 6, in which only the first gate is open, has a slightly less filling time (12.5 seconds) than experiment 7, in which only the last gate is open (13.6 seconds). This can be attributed to the fact that the gates closer to the sprue receive metal earlier than other gates, and also have a higher velocity of flow due to lower flow losses (owing to shorter distance of flow). The difference in filling time is less apparent in centre sprue arrangement because of a more balanced flow, as seen in Table 2.

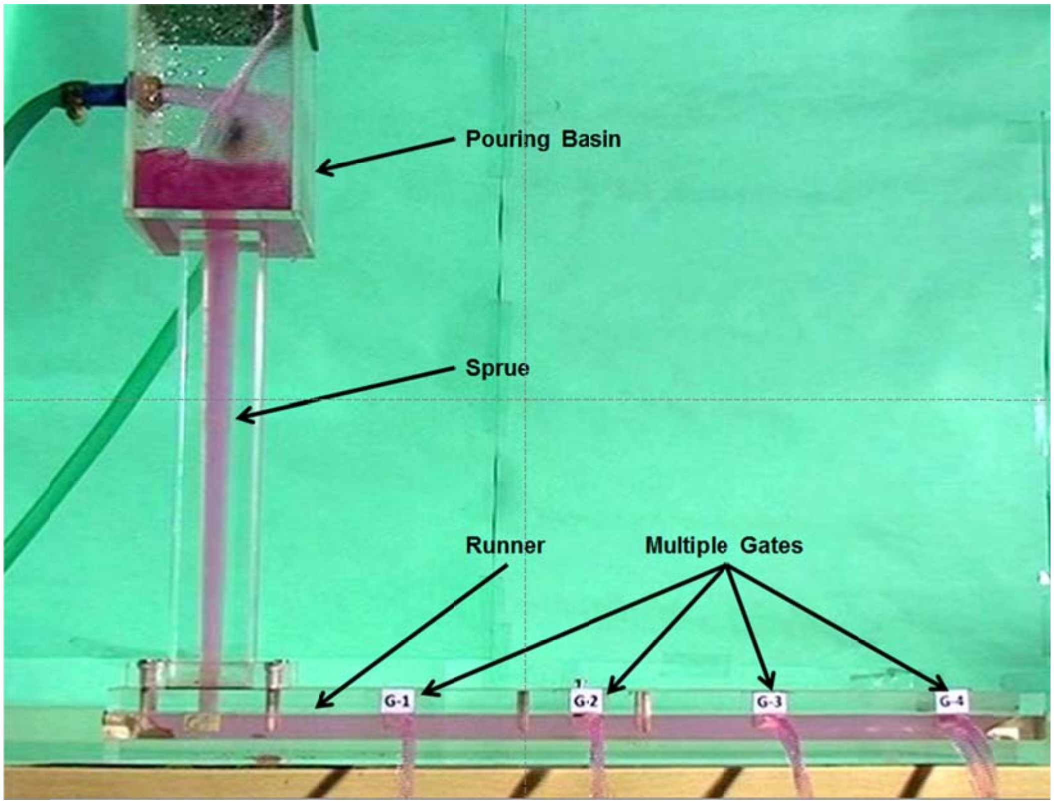


Figure 2: Experimental setup - end sprue arrangement

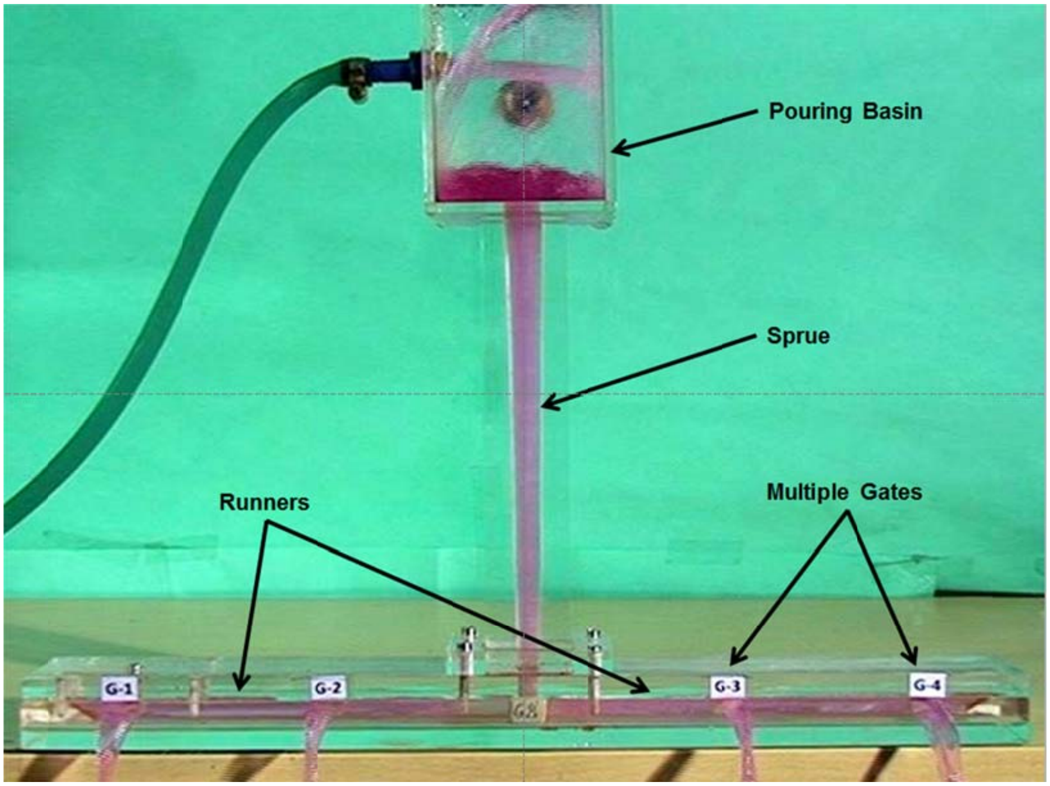


Figure 3: Experimental setup - centre sprue arrangement

Table 1: Results of experiments with end sprue arrangement

Expt. Number	Volume through gates (cm^3)				Time (sec)
	Gate 1	Gate 2	Gate 3	Gate 4	
1	340	418	506	736	9.9
2	468	657	Closed	875	9.8
3	470	Closed	660	870	9.9
4	888	Closed	Closed	1112	11
5	Closed	854	Closed	1146	10.7
6	2000	Closed	Closed	Closed	12.5
7	Closed	Closed	Closed	2000	13.6

Table 2: Results of experiments with centre sprue arrangement

Expt. Number	Volume through gates (cm^3)				Time (sec)
	Gate 1	Gate 2	Gate 3	Gate 4	
1	630	412	385	573	9.5
2	744	Closed	492	764	10.1
3	754	486	Closed	760	8.9
4	Closed	844	466	690	9.1
5	740	485	775	Closed	9.4
6	1025	Closed	Closed	975	9.9
7	Closed	1038	962	Closed	9.5

The discharge (flow rate) through different gates, when all the gates are open, is observed to be the highest in the gate farthest to sprue and least in the gate closest to the sprue as seen by the calculated results in Table 3. In the end sprue arrangement with all gates open (experiment 1), the flow through gate 4, which is the farthest from the sprue, is more than twice the flow through gate 1, which is the nearest to the sprue. If one or more gates are closed, then there is obviously more discharge through the open gates, compared to the discharge when all gates are open. In experiments 6 and 7, the discharge through the single open gate is about twice the highest discharge (through the last gate) when all gates are open.

In the centre sprue arrangement with all gates open (experiment 1), the flow through gates 1 and 4 (farthest from sprue) is about 50% more than the flow through gates 2 and 3 (closest to sprue). The flow is fairly mirrored on both sides of the sprue, as seen in Figure 4. When one of the gates nearest to the sprue is closed (experiments 2 and 3), then the discharge through the remaining gates increases by 20-25%. This imbalance in discharge can be observed from the plot shown in Figure 5. Another observation is that the velocity is the highest in the gate nearest to the sprue, and the lowest in the gate farthest from the sprue.

Table 3: Discharge through different gates in the two setups

Expt. Number	End sprue arrangement Discharge through gates (cm^3/s)				Centre sprue arrangement Discharge through gates (cm^3/s)			
	Gate 1	Gate 2	Gate 3	Gate 4	Gate 1	Gate 2	Gate 3	Gate 4
1	34.4	42.2	51.1	74.4	65.8	43.1	40.3	60
2	47.6	66.8	Closed	88.9	84.4	54.5	Closed	85.2
3	47.4	Closed	66.3	87.8	73.6	Closed	48.7	75.6
4	88.5	Closed	Closed	110.7	Closed	92.7	51.2	75.8
5	Closed	84.4	Closed	113.4	78.7	51.7	82.4	Closed
6	159.3	Closed	Closed	Closed	102.9	Closed	Closed	97.8
7	Closed	Closed	Closed	146.6	Closed	108.5	100.8	Closed

Figure 4: Velocity trend in centre sprue arrangement (video grab)

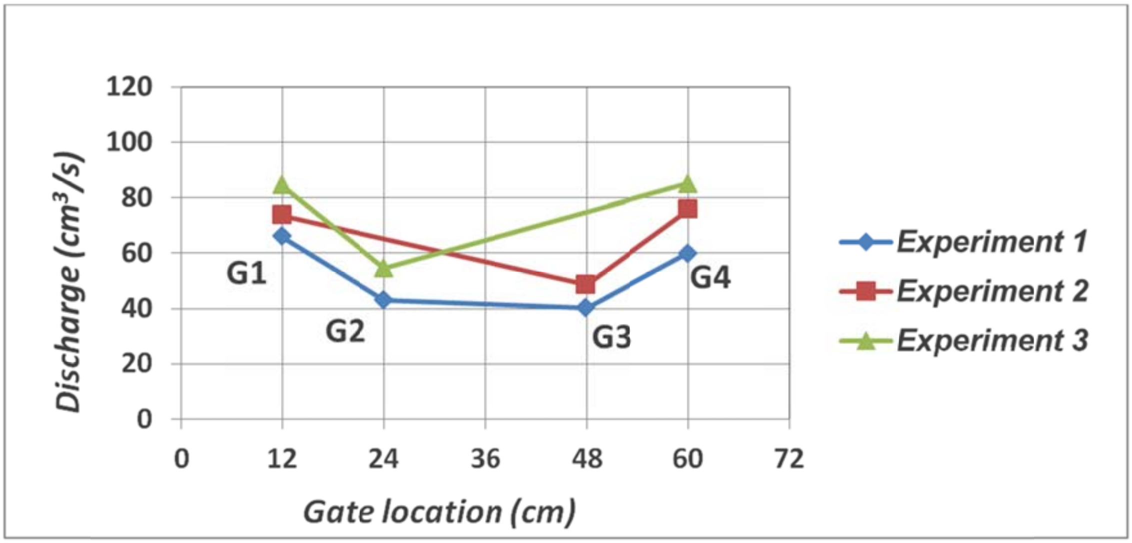


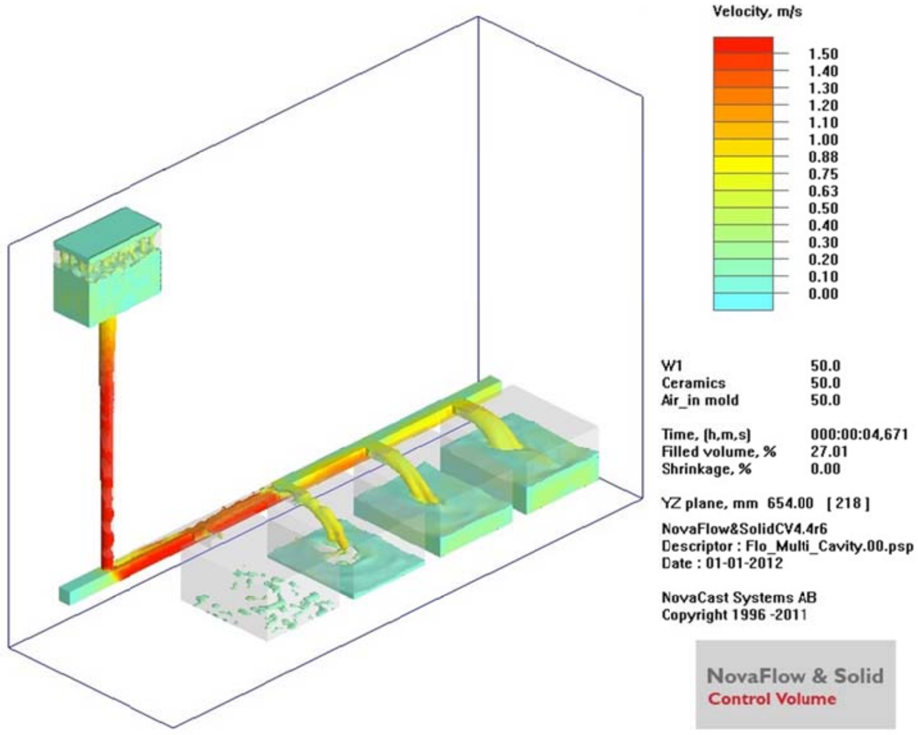
Figure 5: Discharge through gates in centre sprue arrangement

3. Numerical Simulation

Numerical simulation is performed by solving Navier-Stokes equations. This consists of mass, momentum and energy equations, which are simultaneously solved to analyze fluid flow or a coupled fluid and thermal behavior. A number of numerical codes exist today, many of which are commercially available. In this work simulation was performed using NovaFlow (Novacast AB, Sweden), which is based on control volume method (Novacast, 2012).

Various steps in computer simulation include volume discretization, applying boundary conditions (inlet, outlet and wall), defining materials and their properties, choosing a viscous flow model, computation and solution monitoring, and generating the reports of results.

Simulations are performed using 3D CAD models of the multi-gate gating system used for experiments, corresponding to end sprue and centre sprue arrangements (Figure 6 and 7). In simulation too, water was taken as the filling fluid. The values of discharge obtained from experiments and simulation are compared in Table 4. The trend of discharge is the same in both end sprue and centre sprue arrangements: higher in gates farther from the sprue. In the end-sprue arrangement, discharge from the farthest gate is about twice the discharge from the nearest gate, and in the centre sprue arrangement, discharge from the farther gate is about 50% higher that the gate nearer to the sprue. This trend matches the experimental observations. The absolute values of simulated discharge are however, 20-30% higher than the corresponding experimental values. It is to be noted that each cavity has a different filling time owing to different distance of the corresponding gates from the sprue. There is very little discharge in the gates nearer to sprue until the end cavities are filled. There could also be some limitations in the simulation model.



W1 50.0
Ceramics 50.0
Air_in mold 50.0

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Filled volume, % 27.01
Shrinkage, % 0.00

YZ plane, mm 654.00 [218]

NovaFlow&SolidCV4.4r6
Descriptor : Flo_Multi_Cavity.00.psp
Date : 01-01-2012

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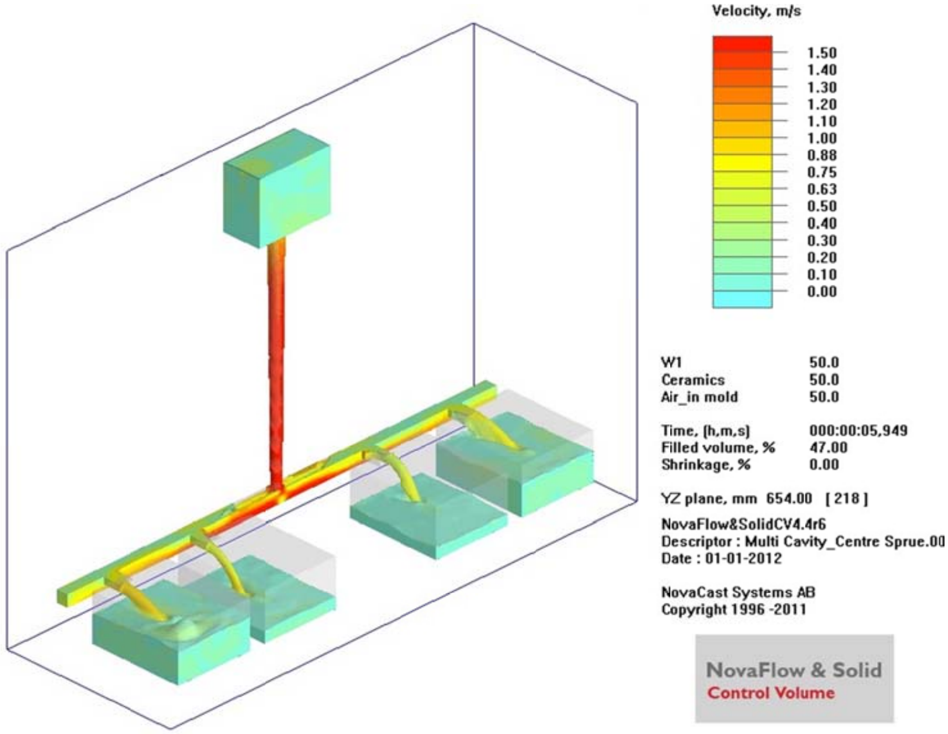
Figure 6: Velocity distribution corresponding to color plot shown in legend



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YZ plane, mm 654.00 [218]

NovaFlow&SolidCV4.4r6
Descriptor : Multi Cavity_Centre Sprue.00
Date : 01-01-2012

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Figure 7: Velocity distribution corresponding to color plot shown in legend

Table 4: Discharge through different gates from experiment and simulation

	End sprue arrangement Discharge through gates (cm^3/s)				Centre sprue arrangement Discharge through gates (cm^3/s)			
	Gate 1	Gate 2	Gate 3	Gate 4	Gate 1	Gate 2	Gate 3	Gate 4
Expt.	34.4	42.2	51.1	74.4	65.8	43.1	40.3	60
Sim.	51	60	72	90	80	55.4	55.4	80
Error	32%	30%	29%	17%	18 %	22%	27%	25%

4. Conclusion

Experimental observations in horizontal multi-gate system show that the trend in discharge (higher in gates farther from the sprue) matches that in previously published literature. In the case of four gate systems, with equal area of gate cross section, and constant area of runner cross section, the ratio of discharge between the different gates has been established. Similar ratios have also been obtained through simulation. However, the absolute values of discharge showed significant error in simulation, pointing to the need to improve the simulation model. There is also a need to correctly predict the values of velocity through different gates.

The current work could be extended by conducting more experiments with different ratios of cross section areas of gates and runners, varying cross section areas of runner (reducing after each gate), and full/partial venting. These results can be used to develop more accurate mathematical and simulation models, which will be useful to design and optimize the gating systems in the industry.

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