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Prediction of Gas Flow Directions in Gas Assisted Injection Molding When Cavities and Runners Are Involved

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Abstract−In the prediction of gas flow-direction for gas-assisted injection molding (GAIM), the statement "Gas goes to the direction of the last area to fill with resin" has been accepted as a correct one. When there exists more than one area to fill with resin, a mold design engineer for GAIM technologies has to determine to which direction gas goes that commercial software for GAIM (e.g., Moldflow) may be utilized for its mold design. However commercial software is generally expensive and is sometimes hard to become familiar with. As a rule of thumb, it is suggested that the resistance to the initial velocity of melt polymer at the nearest geometry to a gas injection point should be used as its criterion since gas goes in the direction of least resistance to initial resin-velocity. Neither the flow rate nor the resistance to flow rate can be a criterion in the prediction. Thus the statement "Gas goes to the direction of the least resistance to flow rates" should be corrected to "More flow rate goes to the direction of the least resistance to flow rates." The rule of thumb suggested in this paper was verified by using commercial software, Moldflow, in the prediction of gas flow directions in GAIM under geometries where cavities and runners were involved. When the ratio of initial resin-velocity is so close to unity it is proposed as the adapted rule of thumb to calculate new emerging resin-velocities and resistances to resin-velocity at the first coming change of diameters in series of pipes and to compare those for upper and lower sides each other to predict the gas direction. Thus the judgment as to which point is the point where gas starts to choose a preferred direction is very important in the prediction.

Key words: Gas Assisted Injection Molding, Rule of Thumb, Preferred Direction of Gas, The Least Resistance to Initial-Resin Velocity

INTRODUCTION

In gas-assisted injection molding (GAIM), gas should flow towards the intended directions. If a gas goes in the wrong direction, many problems occur including a phenomenon called "blow through" and another phenomenon called "penetration into thin walled region". If the gas does not enter where it is expected, a problem like sink mark occurs. The control of gas direction is thus one of the most critical aspects in the application of the technology.

Many researchers [Chen et al., 1995; Khayat et al., 1995; Chen et al., 1996a, b; Gao et al., 1997; Shen, 1997, 2001; Parvez et al., 2002] have investigated primary and secondary gas penetration in terms of gas-liquid interface and polymer melt front in GAIM. Chen et al. [1995] performed both experimental investigation and numerical simulation on the characteristics of the secondary gas penetration in a spiral tube during GAIM. Khayat et al. [1995] simulated the primary gas penetration stage of GAIM process using the Eulerian boundary-element approach. Chen et al. [1996a, b] studied gas and melt flow on GAIM for the design of a thin plate/angle bracket part with a gas channel with numerical simulations using control volume/finite element method. Gao et al. [1997] developed a numerical model capable of predicting the gas penetration using multiple gas-injection units. Shen [1997] develop a model to predict the gas-liquid interface and polymer melt front of a generalized Newtonian fluid in GAIM. Later Shen [2001] developed an algorithm for commercial software to predict the polymer melt front, gas front and solid layer in GAIM. Pavrez et al. [2002] carried out computer simulation of the GAIM process using Moldflow, a commercial software, and compared its outcome with the experimental results. However, their approach cannot be regarded as a rule of thumb but was close to the way of commercial software for GAIM in that numerical simulations were performed by the use of control volume/finite element method or boundary-element approach.

It is a well-known rule of thumb that the prerequisite condition for gas flow is the existence of an unfilled region or short shot at the moment of gas injection. "Gas goes to the direction of the last resin fill area" is a very common statement to many GAIM engineers and mold/part designers. Once this unfilled region exists, gas flows to that direction. However when there exists more than one area to fill with resin, the mold design engineer for GAIM technologies has to determine the direction the gas goes so that commercial software for GAIM (e.g., Moldflow) may be utilized for its mold design. However, commercial software is generally expensive and is sometimes hard to become familiar with. The goal of this paper is to suggest a rule of thumb for predicting a gas direction in GAIM, which is very important information. When there exists more than one unfilled region and these paths are competing for the direction of the gas, it has been believed that the gas preferred the direction of the least resistance. In other words, during the injection stage the gas usually takes the path of least flow resistance to catch up with the melt front. [Chen et al., 1996a, b] Thus "Gas goes to the direction of the least resistance" has been another common statement to GAIM experts.

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The rule of thumb on the direction of gas flow for GAIM has been investigated [Lim and Soh, 1999; Soh, 2000; Soh and Lim, 2002] and simulation packages have been used to verify the gas direction predicted by the rule of thumb. Soh [2000] used a pressure drop requirement as a variable for the resistance of gas directions where the resistance of gas flow was proportional to the pressure drop requirement to keep velocities to both sides the same. Upon comparing pressure drops of both sides, gas directions are predicted to the side of the lower pressure drop. In complex situations, however, this method is hardly applicable. Lim and Soh [1999] assumed that the pressure difference between a gas injection point and appropriate vent areas at both sides of well-maintained molds is equal. Consequently, the pressure drops at both sides are equated to compare the resistances and to predict the gas direction.

If the resistance in the sentence of “Gas goes to the direction of the least resistance” is the resistance to flow rates, this statement is not always correct. The resistance to flow rates cannot be a criterion in the prediction of gas flow direction in GAIM. Soh [2000] qualitatively treated the special case that the same resistances to flow rates for both sides resulted in the same flow rates for both sides under the geometry that two same sets of two different pipes connected in series are located in parallel. Soh and Lim [2002] suggested the definition of the resistance to velocity to predict the gas-preferred direction under the simplest geometry of two different pipes connected at one connection point. However, if more complicated geometries are involved, the change of velocity of melt resin becomes unavoidable. Therefore, as a rule of thumb, a more developed and precise definition of the resistance to velocity should be established. In such a complex situation as runners or thick cavity of two square plates connected to cavities composed of four pipes with same length and different diameter connected in series and parallel, the authors propose a developed concept of a criterion in the prediction of gas flow direction of GAIM as the resistance to the initial velocity of melt polymer at the nearest geometry to a gas injection point in this paper; they show why the comparison of the resistances to flow rates of resin often leads to a wrong prediction for the gas direction, while the comparison of proposed resistances herein generally leads to a valid prediction of gas-preferred direction. In particular, some exceptional cases shall be treated in this paper in which the ratio of initial velocities becomes so close to unity that a gas-preferred direction is initially unstable and the gas direction would be finally reversed to the other direction. For those cases the adapted rule of thumb shall be introduced to predict the final gas direction.

METHODS

1. Theory

The steady state flow of a pseudo plastic liquid through conduit with the radius of R is given by

$$\frac{\Delta p}{2L} = \left[\frac{Q(3n+1)}{\pi n}\right]^n \left[\frac{m}{R^{(3n+1)}}\right] \tag{1}$$

where

m, n=power law indices

L=length of pipe in direction of flow

R=pipe radius excluding frozen layers adjacent to mold surface

Δp=pressure drop across the distance

The Newtonian viscosity, μ, and unity may be substituted, respectively, for m and n in Eq. (1) and the expression of pressure drop of the steady state flow of a Newtonian liquid through a conduit with diameter of D is given in terms of average velocity V as Eq. (2) by McCabe et al. [1986]

$$\Delta p = \frac{32\pi VL}{D^2} \tag{2}$$

Eq. (2) may be rewritten in terms of flow rate Q as

$$\Delta p = \frac{128\mu LQ}{\pi D^4} \tag{3}$$

2. Resistance of Four Conduits with Same Length and Different Diameter Connected in Series and Parallel

Fig. 1-cav shows a cavity composed of two pipes, pipe 1 and pipe 2, connected in parallel. Thick cavities of two square plates are attached to each side of these pipes. Pipe 1 is composed of pipe 11 and pipe 12 connected in series, and pipe 2 is composed of pipe 21 and pipe 22. These four pipes have the same length and may or may not have the same diameter. The polymer and gas injection points are located at the center of the front side of a thick cavity between two square plates in the left hand side. Pipe 1 is located at the up-

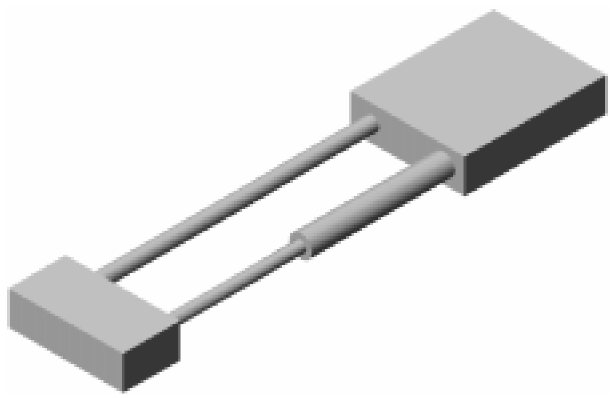

Fig. 1-cav. A cavity composed of two pipes, pipe 1 and pipe 2, connected in parallel. Thick cavities of two square plates are attached to each side of these pipes.

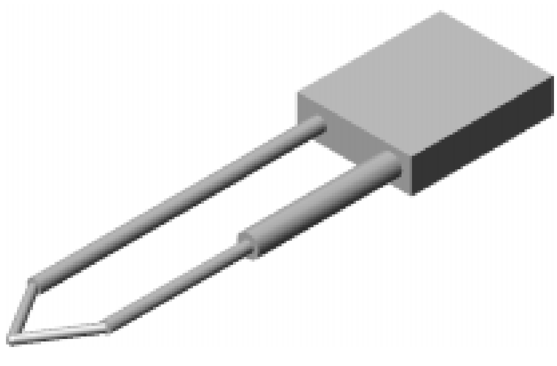

Fig. 1-run. A cavity composed of two pipes, pipe 1 and pipe 2, connected in parallel. At the left side of these pipes branching runners are replaced for a thick cavity of two square plates to deliver resin to both sides of pipes.

per side and pipe 2 is at the lower side. In this paper subscript 11 and subscript 12 denote the first pipe and the second pipe from the left hand side at the upper side, respectively, while subscript 21 and subscript 22 denote the first pipe and the second pipe from the left hand side at the lower side, respectively. For pipe 1 the pressure drop of Δp_1 is:

$$\Delta p_1 = Q_1(r_{11}+r_{12}) = Q_1 r_1 \tag{4}$$

For pipe 2 the pressure drop of Δp_2 is:

$$\Delta p_2 = Q_2(r_{21}+r_{22}) = Q_2 r_2 \tag{5}$$

Since pipe 1 and pipe 2 are connected in parallel, Eqs. (4) and (5) become:

$$\Delta p = \Delta p_1 = \Delta p_2 \tag{6}$$

$$(Q_1+Q_2) r_t = Q_1 r_1 = Q_2 r_2 \tag{7}$$

Thus

$$\frac{Q_1}{Q_2} = \frac{r_2}{r_1} \tag{8}$$

where

$$r_1 = r_{11} + r_{12} = \frac{128\mu}{\pi}\left(\frac{L_{11}}{D_{11}^4} + \frac{L_{12}}{D_{12}^4}\right) \tag{9}$$

$$r_2 = r_{21} + r_{22} = \frac{128\mu}{\pi}\left(\frac{L_{21}}{D_{21}^4} + \frac{L_{22}}{D_{22}^4}\right) \tag{10}$$

3. Definition of Proposed Resistance

The definition of resistance may be develped and proposed to be r^* as a resistance to V^* of the initial velocity of melt polymer at the nearest geometry to a gas injection point while the resistance to flow rate was previously defined as r. Consequently, the proposed resistance of steady state flow of a Newtonian liquid under the geometry as in Fig. 1-cav may be rearranged as below.

$$\Delta p_1 = Q_1 r_1 = V^* r_1^* = V_{11} r_1^* \tag{11}$$

$$\Delta p_2 = Q_2 r_2 = V^* r_2^* = V_{21} r_2^* \tag{12}$$

where

$$r_1^* = \frac{\pi}{4} D_{11}^2 r_1 = 32\pi D_{11}^2\left(\frac{L_{11}}{D_{11}^4} + \frac{L_{12}}{D_{12}^4}\right) \tag{13}$$

$$r_2^* = \frac{\pi}{4} D_{21}^2 r_2 = 32\pi D_{21}^2\left(\frac{L_{21}}{D_{21}^4} + \frac{L_{22}}{D_{22}^4}\right) \tag{14}$$

Thus

$$\frac{r_2^*}{r_1^*} = \frac{r_2 D_{21}^2}{r_1 D_{11}^2} \tag{15}$$

RESULTS AND DISCUSSION

1. Situation When Cavities of Pipes and Thick Plates are Involved in Configuration

1-1. Case of cav-1

In Fig. 2, at the upper side, pipe 11 with a diameter of 5 mm and a length of 50 mm is connected to pipe 12 with the same diameter and the same length as pipe 11. At the lower side, pipe 21 with a diameter of 8 mm and a length of 50 mm is connected in series to pipe 22 with a diameter of 4 mm and a length of 50 mm.

Consider a situation where a resin fluid is flowing to the direction of right hand side at steady state. The relation between the pressure drop, flow rate, and the dimensions of pipe 1 is:

$$\Delta P_1 = Q_1 \frac{128\mu L_1}{\pi D_1^4} \tag{16}$$

Substitution of diameter and length of pipe 1 gives:

$$\Delta P_1 = Q_1 \frac{128\mu}{\pi}(0.16) \tag{17}$$

$$\Delta P_1 = Q_1 r_1 \tag{18}$$

The resistance to flow rate is:

$$r_1 = \frac{128\mu}{\pi}(0.16) \tag{19}$$

For pipe 2:

$$\Delta P_2 = Q_2\left(\frac{128\mu L_{21}}{\pi D_{21}^4} + \frac{128\mu L_{22}}{\pi D_{22}^4}\right) \tag{20}$$

Substitution of diameter and length of pipe 2 gives:

$$\Delta P_2 = Q_2 \frac{128\mu}{\pi}(0.207) \tag{21}$$

$$\Delta P_2 = Q_2 r_2 \tag{22}$$

The resistance to flow rate is:

$$r_2 = \frac{128\mu}{\pi}(0.207) \tag{23}$$

Since Δp_1 is equal to Δp_2 from Eq. (6)

$$\frac{Q_1}{Q_2} = 1.297 \tag{24}$$

$$\frac{r_2}{r_1} = \frac{Q_1}{Q_2} \tag{25}$$

Thus

$$\frac{r_2}{r_1} = 1.297 \tag{26}$$

This result shows that the resin flow rate is higher and the resistance to flow rate is lower at the upper side pipe 1. Now consider a case where the nitrogen gas is injected into the gas injection point after both pipe 1 and pipe 2 are completely filled and a thick cavity between two square plates in the right hand side is partially filled. One could jump to the conclusion that pipe 1 is the preferred path for the gas as its flow rate is higher and its resistance is smaller, but let us first compare velocities at these two points.

In terms of initial resin velocity its pressure drop may be expressed as:

$$\Delta P_1 = V_1 r_1^* \tag{27}$$

where $r_1^* = \left(\frac{\pi}{4}\right) D_1^2 r_1$

$$\Delta P_2 = V_{21} r_2^* \tag{28}$$

where $r_2^* = \left(\frac{\pi}{4}\right) D_{21}^2 r_2$

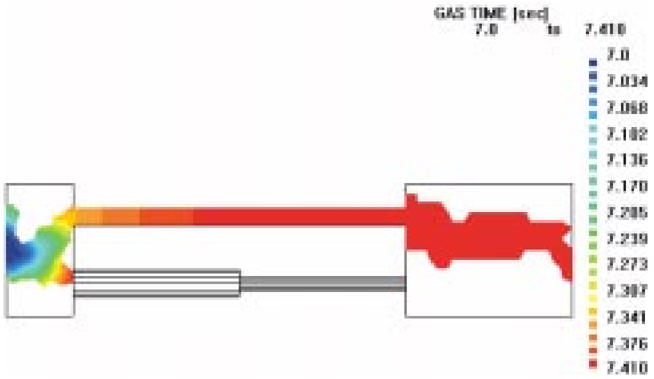

Fig. 2. Case of cav-1: Pipe 11 with a diameter of 5 mm and a length of 50 mm is connected to pipe 12 with a diameter of 5 mm and a length of 50 mm. Pipe 21 with a diameter of 8 mm and a length of 50 mm is connected in series with pipe 22 with a diameter of 4 mm and a length of 50 mm.

Then the initial velocity ratio between pipe 11 and pipe 21 is

$$\frac{V_1}{V_{21}}=\frac{r_2^*}{r_1^*}=\frac{r_2 D_{21}^2}{r_1 D_1^2} \tag{29}$$

Thus

$$\frac{r_2^*}{r_1^*}=3.32 \tag{30}$$

When the gas chooses its preferred direction between pipe 11 and pipe 21 at the entrance of these pipes, it seems that the gas prefers the upper pipe. The upper pipes have a higher flow rate, a lower resistance to flow rates, and a higher initial velocity of the resin than the lower pipes. In that situation the fact that resin flow rate was higher in pipe 1 did not lead us to the prediction of the gas direction, but the fact that pipe 1 had a higher initial velocity led to the prediction of the gas direction. It was purely coincident that the path with a higher flow rate was characterized as that with higher initial resin velocity. Thus the prediction of gas direction should not come from the comparison of resistance to flow rates either.

Fig. 2 shows a simulation result of commercial software, Moldflow, that is consistent with the prediction that the gas did not pass through pipe 2 but through pipe 1. In the figure, all the white region represents the cavity with 100% polymer, and the colored regions represent the cavity where gas entered. The gas time in the colored region shows the time when the gas was reached.

1-2. Case of cav-2

One may use the same pipes and flip the lower pipes horizontally, as shown in Fig. 3. For pipe 1, the pressure drop is:

$$\Delta P_1=Q_1\frac{128\mu}{\pi}(0.16) \tag{31}$$

and the resistance to flow rate is:

$$r_1=\frac{128\mu}{\pi}(0.16) \tag{32}$$

For pipe 2:

$$\Delta P_2=Q_2\left(\frac{128\mu L_{21}}{\pi D_{21}^4}+\frac{128\mu L_{22}}{\pi D_{22}^4}\right) \tag{33}$$

Substituting dimensions of pipe 21 and 22,

$$\Delta P_2=Q_2\frac{128\mu}{\pi}(0.207) \tag{34}$$

and

$$r_2=\frac{128\mu}{\pi}(0.207) \tag{35}$$

Substituting Eq. (31) and Eq. (34) into Eq. (6),

$$\frac{Q_1}{Q_2}=\frac{r_2}{r_1}=1.297 \tag{36}$$

This result shows the same flow rate ratio, Q_1/Q_2, and the resistance ratio, r_2/r_1, as the case shown in the case of cav-1. The flow rate is higher at pipe 1. However, one should not jump to the conclusion that gas may go through pipe 1 yet. At this point, let us compare the initial resin velocities at the entrance of the pipes.

$$\frac{V_1}{V_{21}}=\frac{r_2^*}{r_1^*}=\frac{r_2 D_{21}^2}{r_1 D_1^2} \tag{37}$$

Thus

$$\frac{r_2^*}{r_1^*}=0.830 \tag{38}$$

The resin flow rate inside pipe 1 is higher. However, the resin velocity inside pipe 1 is lower than that inside pipe 21, which is the first part of the lower side pipes. One should not use the resin flow rate but use the initial velocities to predict the gas direction since the gas bubble is first seen in the direction of higher velocity. Once the gas comes in, the effective length in Eq. (2) becomes smaller due to accumulation of the frozen layer in mold cavities, which amplifies the differences between velocities. Thus, gas would not go through the path with the higher flow rate or the lower resistance to flow rates but through the path with the higher initial resin velocity. The simulation result of Moldflow shows that gas goes through pipe 2 in Fig. 3. This case shows an example where the least resistance to initial resin velocity should be a required condition to determine the gas flow directions instead of that to flow rates.

When the lower pipes were flipped, as is from the case of cav-1, the ratio of resistances to flow rates, r_2/r_1, was not changed. Thus

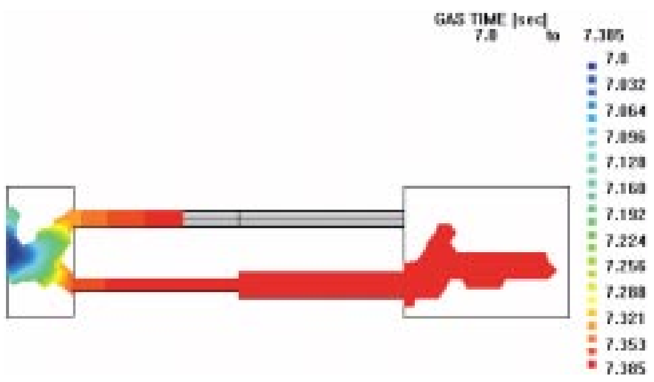

Fig. 3. Case of cav-2: The geometry is the same as Fig. 2 except that lower pipes were flipped horizontally. Flipping the lower pipes caused gas path to change.

the ratio of resistances to flow rates in the case of cav-2 is the same as in the case of cav-1 since the rato of flow rates, Q_1/Q_2, in the case of cav-2 is also the same as in the case of cav-1. However, the ratio of resistance to initial velocity, r_2^*/r_1^*, in the case of cav-2 is not the same as in the case of cav-1. Thus, this ratio of resistances to initial velocity or the velocity difference dictates the direction of gas flow.

2. Situation When Cavities of Pipes and Runners are Involved in Configuration

2-1. Case of run-1:

Fig. 1-run shows a cavity composed of two pipes, pipe 1 and pipe 2, connected in parallel. At the left side of these pipes branching runners are replaced for a thick cavity of two square plates to deliver resin to both sides of the pipes. The length (L_1') and the diameter (D_1') of the runners at the upper side of pipes are 51 mm and 3 mm, respectively. The same geometric condition is applied to the runner at the lower side of the pipes. Here prime (') denotes runners connected to the pipes. In this situation, the gas has to choose the preferred direction between pipe 1 and pipe 2 at the dividing point of the runners or the gas injection point. Thus, velocities to two directions at this dividing point should be compared.

For the upper part,

$$r_1' = \frac{128\mu}{\pi}(0.629) \tag{39}$$

$$r_1' = \frac{128\mu}{\pi}(0.16) \tag{40}$$

where r_1' and r_1 are the resistance of a runner to pipe 1 and the resistance of pipe 1, respectively. Pipe 1 does not include the runner.

Total resistance to flow rates at the upper side including runner, r_U, is:

$$r_U = \frac{128\mu}{\pi}(0.790) \tag{41}$$

The resistance to flow rates of runner at the lower side is:

$$r_2' = \frac{128\mu}{\pi}(0.629) \tag{42}$$

The resistance to flow rates of pipe 21 is:

$$r_{21} = \frac{128\mu}{\pi}(0.0122) \tag{43}$$

The resistance to flow rates of pipe 22 is:

$$r_{22} = \frac{128\mu}{\pi}(0.195) \tag{44}$$

Total resistance to flow rates at the lower side including runner, r_L, is:

$$r_L = \frac{128\mu}{\pi}(0.837) \tag{45}$$

$$\frac{Q_U}{Q_L} = \frac{r_L}{r_U} = 1.060 \tag{46}$$

This result shows that the resistance to flow rates is lower and the flow rate is higher in pipe 1 at the upper side. The velocity ratio at the runners is

$$\frac{V_1'}{V_2'} = \frac{Q_U(D_2')^2}{Q_L(D_1')^2} \tag{47}$$

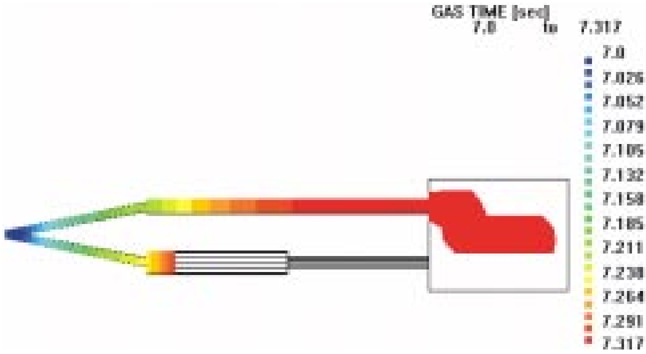

Fig. 4. Case of run-1: The geometry is similar to Fig. 2. Instead of a thick cavity of two square plates, this cavity has branching runners at the left hand side to deliver resin to pipes at both upper side and lower side.

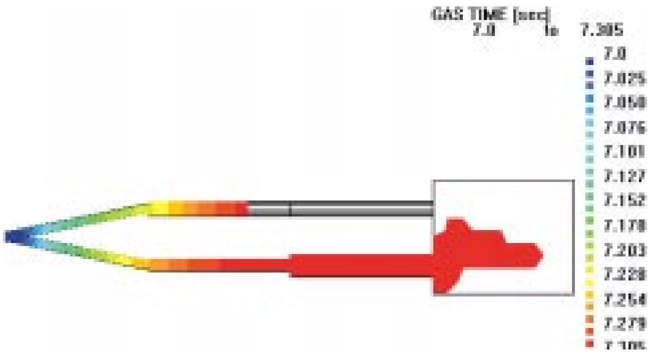

Fig. 5. Case of run-2: The geometry is the same as Fig. 4 except that lower pipe was flipped horizontally. Flipping the lower pipes caused gas path to change.

Since D_1' and D_2' are the same, the ratio of resistances to initial resin-velocity is the same as the ratio of resistances to flow rates.

$$\frac{r_2^*}{r_1^*} = 1.060 \tag{48}$$

Since the resistance to initial resin-velocity at the upper runner is lower than that at the lower runner, it is predicted that the gas would enter the upper runner. The simulation result of Moldflow confirms the prediction as in Fig. 4.

2-2. Case of run-2

In Fig. 5, a similar situation to the case of cav-2 as in Fig. 3 is shown. Instead of the thick cavity of two square plates, Fig. 5 has branching runners at the left hand side. One may use the same configuration as shown in Fig. 4 but flip the lower pipe horizontally as shown in Fig. 5. In this case the ratio of resistances to flow rates as well as the ratio of resistances to initial resin velocity is identical to those in the case of run-1.

$$\frac{Q_U}{Q_L} = \frac{r_L}{r_U} = 1.060 \tag{49}$$

$$\frac{V_1'}{V_2'} = \frac{Q_U(D_2')^2}{Q_L(D_1')^2} \tag{50}$$

$$\frac{r_2^*}{r_1^*} = 1.060 \tag{51}$$

The use of the same diameter of runners at the upper and lower sides resulted in the ratio of r being identical to that of r^*. Thus, the ratio of r^* of both sides would not be close to unity unless the same diameter was used for the upper and lower runners, which is shown in the following case of run-3. Since r^* inside the upper runner is lower than that in the lower runner, one might predict that the gas would again enter the upper runner like the previous case of run-1. However, the result of simulation of Moldflow goes contrary to the prediction as shown in Fig. 5. In this case the ratio of r^* is so close to unity because initial resistance r^* at upper side is a little bit lower than r^* at lower side that gas direction is prone to change to lower side whenever the on-going velocity of resin at the lower side obviously exceeds that at the upper side. In the case of run-1 the velocity of resin at the upper side runner is a little bit higher than that at a lower side runner, and the velocity of resin at upper side obviously gets higher than that at the lower side when gas penetrates the upper pipe (D_1=5 mm) and the lower pipe (D_{21}=8 mm) that gas direction would not change. On the other hand, in the case of run-2 gas direction is shifted from the upper side's pipe (D_1=5 mm) to the lower side's pipe (D_{21}=4 mm) when gas penetrates the first pipe (D_{21}=4 mm) at the lower side as shown in Fig. 5. Thus when the ratio of r^* was so close to unity like the case of run-2 it is proposed to calculate new emerging resin-velocities and resistances to velocity for the first coming change of diameters in series of conduits and to compare those for upper and lower sides with each other to predict the gas direction.

2-3. Case of run-3

The configuration of this case was the same as the case of run-1 except for the size of diameter of the lower runner (D_2') and the lower first pipe (D_{21}). D_2' and D_{21} are given as 4 mm and 3.26 mm, respectively, so that the ratio of resistances to flow rates was intended to be the same as that for the case of run-1 and run-2.

$$\frac{Q_U}{Q_L}=\frac{r_L}{r_U}=1.060 \tag{52}$$

$$\frac{V_1'}{V_2'}=\frac{Q_U(D_2')^2}{Q_L(D_1')^2} \tag{53}$$

$$\frac{r_2^*}{r_1^*}=1.88 \tag{54}$$

Since the use of the same diameter of runners at upper and lower sides was avoided in this case, the ratio of r^* of both sides as in Eq. (54) was bigger than the ratio of r as in Eq. (52) which was close to unity. According to Eq. (54), the preferred gas direction is determined to be the upper side and the prediction of gas direction is consistent with the result of simulation of Moldflow as in Fig. 6. Even though the ratio of the resistance to flow rates was close to unity, almost a factor of two differences between both the resistances to initial resin velocity (r^*) determined the preferred gas direction to remain at upper side.

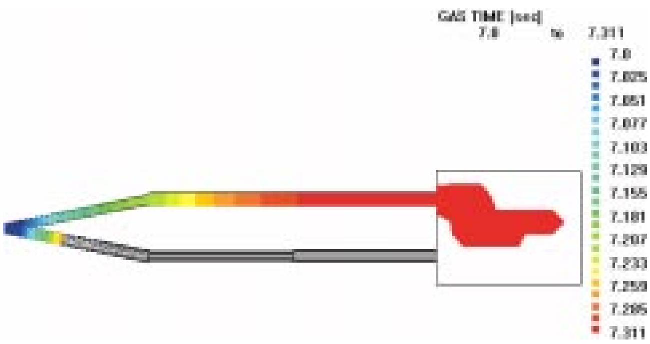

Fig. 6. Case of run-3: The geometry is the same as Fig. 4 except that the size of diameter of lower runner and the lower first pipe are given as 4 mm and 3.26 mm, respectively.

Fig. 7. Case of run-4: The geometry is the same as Fig. 6 except that lower pipe was flipped horizontally. Gas path did not change by flipping the lower pipes.

2-4. Case of run-4:

As in the previous cases, the lower pipes of the case of run-3 were flipped horizontally with each other. The ratio of resistances to flow rates and the ratio of resistances to initial resin velocity were the same as in the case of run-3. Therefore, the gas direction is predicted to the upper side as in the case of run-3. Even though lower pipes (pipe 21 and pipe 22) are flipped horizontally, the predicted gas direction was not changed to remain at the upper side, which is consistent with the result of simulation of Moldflow as in Fig. 7.

2-5. Case of run-5

The configuration of this case was exactly the same as the case of run-3 except for the size of diameter of the lower runner (D_2') and the lower first pipe (D_{21}). D_2' and D_{21} are given as 5mm and 3.07 mm, respectively, so that the ratio of resistances to flow rates was again intended to be the same as that for the case of run-1 and run-2.

$$\frac{Q_U}{Q_L}=\frac{r_L}{r_U}=1.060 \tag{55}$$

$$\frac{V_1'}{V_2'}=\frac{Q_U(D_2')^2}{Q_L(D_1')^2} \tag{56}$$

$$\frac{r_2^*}{r_1^*}=2.94 \tag{57}$$

Even though the ratio of the resistance to flow rates was close to unity, almost a factor of three differences between both the resistances to initial resin velocity (r^*) determined the preferred gas direction to remain at the upper side, which is consistent with the result of simulation of Moldflow as in Fig. 8.

2-6. Case of run-6

As in the previous cases, the lower pipes of the case of run-5 are flipped horizontally with each other. The ratio of resistances to flow rates and the ratio of resistances to initial resin velocity remain as the same as in the case of run-5. Therefore, gas direction is predicted to the upper side as in the case of run-5. Even though lower

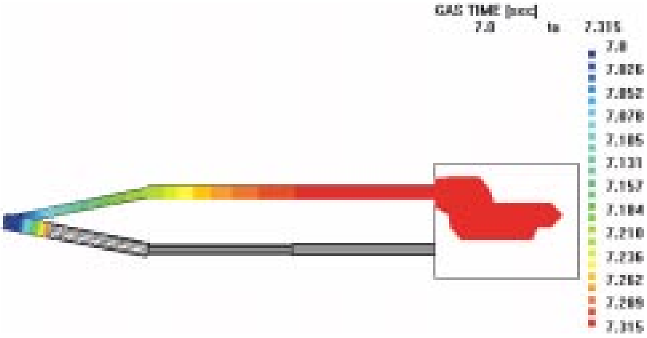

Fig. 8. Case of run-5: The geometry is the same as Fig. 4 except that the size of diameter of lower runner and the lower first pipe is given as 5 mm and 3.07 mm, respectively.

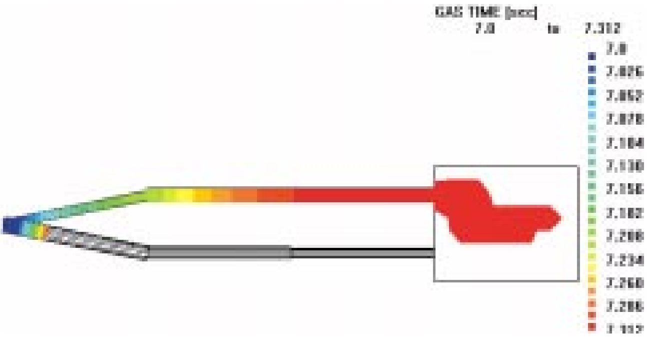

Fig. 9. Case of run-6: The geometry is the same as Fig. 8 except that lower pipe was flipped horizontally. Gas path did not change by flipping the lower pipes.

pipes (pipe 21 and pipe 22) are flipped horizontally, the predicted gas direction was not changed to remain at the upper side, which is consistent with the result of simulation of Moldflow as in Fig. 9.

CONCLUSION

In the case of cav-1 and cav-2, the gas path was predicted to change by flipping the lower side pipe, pipe 2, which was consistent with the result of simulation. Neither the flow rate ratio nor the ratio of resistances to flow rates can be a criterion in the prediction of preferred direction of gas. The resistance to initial resin velocities should be a criterion in the prediction of preferred direction. In the case of run-1 and run-2, on the other hand, the gas path was predicted not to change by flipping the lower side pipe. The predicted gas path for the former was consistent with the result of simulation as in Fig. 4. However, the gas path for the latter was contrary to the simulation result as in Fig. 5. In the case of run-1 and run-2, when the gas is choosing a preferred path at a dividing point, the flow rate ratio or the ratio of resistances to flow rates (r) as well as the ratio of initial resin velocity or the ratio of resistances to initial resin-velocity (r^*) might be considered to be used as a criterion for the prediction, since the cross sectional areas at the dividing point were the same. However, in these cases, the ratio of r^* was very close to unity because initial resistance r^* at the upper side is a little bit lower than r^* at the lower side that gas direction is prone to change to lower side whenever the on-coming velocity of resin at the lower side obviously exceeds that at the upper side. It actually happened in the case of run-2. That is why the result of simulation turned out to be contrary to the prediction in the case of run-2. These results are summarized in Table 1. When the ratio of r^* was very close to unity like the cases of run-1 and run-2, it is proposed to calculate new emerging resin-velocities and resistances to resin-velocity at the first coming change of diameters in series of pipes and to compare those for upper and lower sides to predict the gas direction. Thus, the judgment as to which point is the point where gas starts to choose a preferred direction is very important in the prediction.

Table 1. Prediction of gas direction by the resistance to flow rates (r) and the resistance to the initial velocity of melt polymer at the nearest geometry to a gas injection point

Case	Lower r	Lower r^*	Flow direction (Simulation result)
cav-1	Upper (0)	Upper (0)	Upper (Fig. 2)
cav-2	Upper (X)	Lower (0)	Lower (Fig. 3)
run-1	Upper (0)	Upper (0)	Upper (Fig. 4)
run-2	Upper^c (X)	Upper^c (X)	Lower (Fig. 5)
run-3	Upper^c (0)	Upper (0)	Upper (Fig. 6)
run-4	Upper^c (0)	Upper (0)	Upper (Fig. 7)
run-5	Upper^c (0)	Upper (0)	Upper (Fig. 8)
run-6	Upper^c (0)	Upper (0)	Upper (Fig. 9)

*The superscript of c in Table 1 denotes that its resistance is very close to unity.
* "0" and "X" denote "correct" and "incorrect" respectively.

In the case of run-5 and run-6 as well as run-3 and run-4 it was designed to have the condition that each ratio of resistances to flow rates (r) was close to unity as in the cases of run-1 and run-2 while each ratio of resistances to initial resin velocity (r^*) was two to three times larger than unity, unlike the cases of run-1 and run-2--to confirm if the proposed resistance should be a criterion to predict the gas direction in gas-assisted molding technology. Even though the ratio of resistances to flow rates was close to unity, almost a factor of two to three differences between the resistances to initial resin velocity (r^*) at both sides determined the preferred gas direction to remain at the upper side, which is consistent with the results of simulation as shown in Figs. 6 to 9. This strongly supports that the resistance to initial resin velocities should be a criterion in the prediction of preferred direction.

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NOMENCLATURE

D : diameter of pipe or conduit
D' : diameter of a runner
D^* : diameter of the nearest pipe or conduit to a gas injection point
L : length of pipe in the direction of flow
L' : length of a runner
L^* : length of the nearest pipe to a gas injection point in the direction of flow

m, n : power law indices
Δp : pressure drop along the distance
Q : flow rate
R : pipe radius excluding frozen layers adjacent to mold surface
r : resistance of pipes to flow rates
r_L : total resistance to flow rates at lower side
r_U : total resistance to flow rates at upper side
r_t : total resistance of pipes to flow rates
r' : resistance of runners to flow rates
r^* : resiatance to the initial velocity of melt polymer at the nearest geometry to a gas injection point
V : average velocity
V' : average velocity at a runner
V^* : average velocity of the nearest leading front of melt polymer to a gas injection point

Greek Lettre

μ : Newtonian viscosity

Subscripts

1 : upper side
11 : the first pipe at upper side
12 : the second pipe at upper side
2 : lower side
21 : the first pipe at lower side
22 : the second pipe at lower side

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