Edge Effect in RTM Processes Under Constant Pressure Injection Conditions

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ABSTRACT: In resin transfer molding processes, the edge effect caused by the nonuniformity of permeability between fiber preform and edge channel may disrupt resin flow patterns and often results in the incomplete wetting of fiber preform, the formation of dry spots, and other defects in final composite materials. So a numerical simulation algorithm is developed to analyze the complex mold-filling process with edge effect. The newly modified governing equations involving the effect of mold cavity thickness on flow patterns and the volume-averaging momentum equations containing viscous and inertia terms are adopted to describe the fluid flow in the edge area and in the fiber preform, respectively. The volume of fluid (VOF) method is applied to tracking the free interface between the two types of fluids, namely the resin and the air. Under constant pressure injection conditions, the effects of transverse permeability, edge channel width, and mold cavity thickness on flow patterns are analyzed. The results demonstrate that the transverse flow is not only affected by the transverse permeability and the edge channel width but also by the mold cavity thickness. The simulated results are in agreement with the experimental results. © 2010 Wiley Periodicals, Inc. J Appl Polym Sci 118: 1014–1019, 2010

Key words: resin transfer molding; edge effect; transverse flow; constant pressure injection; numerical simulation

INTRODUCTION

Resin transfer molding (RTM) processes offer the advantages of automation, low cost, and versatile design of fiber reinforcement, which have gained popularity in polymer composite industry. In RTM processes, a fiber preform is cut into the desired shape and preplaced in the mold, then a thermoset resin flows around and through the fiber network until the mold is filled. Since it is difficult to cut the fiber preform precisely, sometimes a clearance is left between the fiber preform and the mold edge. Edge effect occurs because resin travels faster in the clearance than in the fiber preform. The presence of edge effect may disrupt flow patterns and often results in the incomplete wetting of fiber preform, the formation of dry spots, and other defects in final composite materials.[1] The vent is also often affected by the edge effect, because it should be arranged in such a way enabling air evacuation by means of advancing resin flow front. Ideally they should be placed at the region of the mold which is filled last.

Edge effect has been viewed traditionally as an unwanted effect. However, pre-designed air channels can be used to enhance the mold-filling process. The advantages obtained through the controlled use of edge effect include reduction of injection and mold pressures required to fill a mold for constant flow rate injection or shorter mold filling times for constant pressure injection.[2,3]

Both experiments and numerical simulations are implemented to investigate the edge effect. Gupte and Advani[4,5] carried out the experimental investigation of the flow in the close vicinity of the permeable boundary of a porous medium. They found that the boundary layer in the porous medium was of the order of the thickness of the Hele-Shaw cell and not of the order of the permeability of the porous medium as long as the Hele-Shaw approximation was valid.

The equivalent permeability approach has been used frequently to simulate the edge flow in the

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past. Hammami et al.[6,7] proposed two models to calculate the equivalent permeability of the edge channel. The first model assumed that the flow was taking place between parallel plates. In the second model, the flow was assumed to take place in a cylindrical channel. A transverse flow factor was defined to evaluate the amount of transverse flow. They suggested a limit value of the transverse flow factor, above which the transverse flow should be taken into account, and the models were no longer valid. Ni et al.[1] used the equivalent permeability approach and the lumped permeability approach to model the race tracking effects in liquid composite molding. Young and Lai[8] developed an equivalent permeability model to simulate the edge channeling flow under constant pressure injection conditions. Bickerton and Advani[9] studied the edge effect in a planar rectangular mold cavity, which had a single air cavity running along one side of the mold.

At the same time, another approach was adopted, in which the Navier-Stokes equation was used to describe the flow in the edge channel. Costa et al.[10,11] presented the control volume based finite element method for studying the problem, the Navier-Stokes equations and the Brinkman-Forchheimer-extended Darcy equations were used to model the fluid flow in the free medium and the porous medium, respectively. But their studies were limited to steady-state, two-dimensional flow problems, the location, and shape of the flow front at any time were not simulated yet. Yang et al.[12] developed a mathematical model involving the effect of mold cavity thickness on resin flow. The volume-averaging momentum equations containing viscous and inertia terms were adopted to describe the resin flow in the fiber preform, and the modified governing equations derived from the Navier-Stokes equations were introduced to describe the resin flow in the edge channel. The numerical simulation on edge effect under the injection condition of constant flow velocity was carried out.

On the basis of the previous work,[12] the edge effect under constant pressure injection conditions is studied in this article. The effects of transverse permeability, edge channel width, and mold cavity thickness on flow fronts and filling time are analyzed systematically.

CONSTRUCTION OF MATHEMATICAL MODEL

A mold-filling model with an edge channel is constructed in a Cartesian coordinate system, as shown in Figure 1, where the clearance 'd' is the dimension between the mold wall and the fiber preform, and 'h' denotes the thickness of the mold cavity. The condition at the entrance of the mold is a constant injection pressure. The flows in fiber preform and in

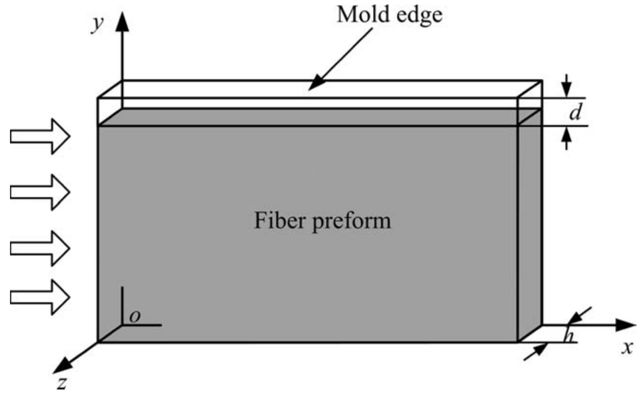

Figure 1 Mold-filling model with an edge channel.

edge channel are modeled as two-phase (resin and air) fluid flows through porous medium and free fluid region, respectively.[12]

Flow in the edge channel

According to the mathematical analysis of the momentum equations in a fully developed rectangular duct and the formulations of an equivalent edge permeability, comparing with three-dimensional Navier-Stokes equations, the governing equations of fluid flow which were derived in detail in Ref. 12 in the edge channel are newly modified as:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho \upsilon u)}{\partial y}=-\frac{\partial p}{\partial x}+\mu\frac{\partial^2 u}{\partial x^2}-\frac{\mu}{K_{\mathrm{me}}}\cdot u \quad (1)$$

$$\frac{\partial(\rho \upsilon)}{\partial t}+\frac{\partial(\rho u\upsilon)}{\partial x}+\frac{\partial(\rho \upsilon\upsilon)}{\partial y}=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 \upsilon}{\partial x^2}+\frac{\partial^2 \upsilon}{\partial y^2}\right) \quad (2)$$

where t denotes time, u and v are velocity components in the x and y direction, p the fluid pressure, ρ the fluid density, K_{me} the equivalent permeability, and μ is the dynamic viscosity.

where

$$K_{\mathrm{me}}=\frac{h^2}{96}\left[1-\frac{192h}{\pi^5 d}\tanh\left(\frac{\pi d}{2h}\right)\right] \qquad d\le h \qquad (3)$$

$$K_{\mathrm{me}}=\frac{d^2}{96}\left[1-\frac{192d}{\pi^5 h}\tanh\left(\frac{\pi h}{2d}\right)\right] \qquad d> h \qquad (4)$$

There are the formulations in each control volume

$$\mu=f\mu_1+(1-f)\mu_2 \qquad \rho=f\rho_1+(1-f)\rho_2 \qquad (5)$$

where the subscripts denote the different fluids.

The fractional volume function is defined as follows:

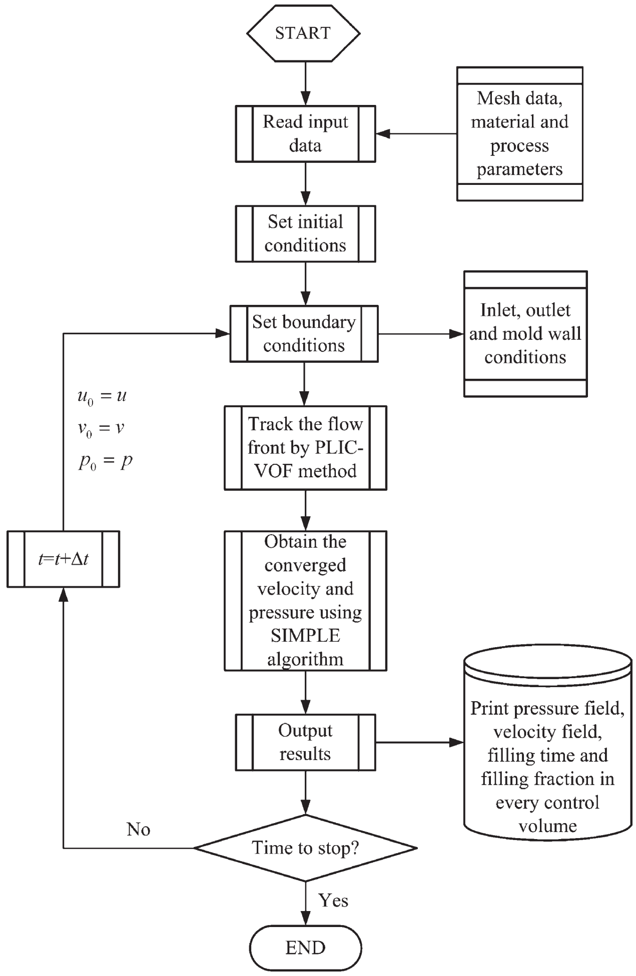

Figure 2 Flow chart of the numerical simulation.

$$f(x,y,t) = \begin{cases} 1 \text{ for the point } (x,y,t) \text{ inside fluid 1} \\ 0 \text{ for the point } (x,y,t) \text{ inside fluid 2} \\ >0, <1 \text{ for the point } (x,y,t) \text{ at the interface} \end{cases} \quad (6)$$

where the fluid 1 denotes the resin, and fluid 2 the air.

The conservation of mass is

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (7)$$

The fractional volume function advection equation is

$$\frac{\partial f}{\partial t} + u\frac{\partial f}{\partial x} + v\frac{\partial f}{\partial y} = 0 \quad (8)$$

where f denotes the volume fraction of resin phase. Equation (8) is used to track the resin flow front.

Flow in the fiber preform

As the fiber preform is a double-scale porous medium, the local volume averaging method is introduced and the average quantities in the field equations are used. In the fiber preform, the conservation of mass is:

$$\frac{\partial\langle u\rangle}{\partial x} + \frac{\partial\langle v\rangle}{\partial y} = 0 \quad (9)$$

Aimed at the limitation of the numerical simulation of RTM process based on Darcy law, viscous and inertia effects in governing equations are considered. The momentum equation in the fiber preform takes the form[12]:

$$\frac{1}{\phi}\frac{\partial(\rho\langle u\rangle)}{\partial t} + \frac{1}{\phi^2}\left[\frac{\partial(\rho\langle u\rangle\langle u\rangle)}{\partial x} + \frac{\partial(\rho\langle u\rangle\langle v\rangle)}{\partial y}\right] = -\frac{\partial\langle p\rangle^f}{\partial x} + \mu_{\text{eff}}\left[\frac{\partial^2\langle u\rangle}{\partial x^2} + \frac{\partial^2\langle u\rangle}{\partial y^2}\right] - \frac{\mu}{K_x}\langle u\rangle$$

$$\frac{1}{\phi}\frac{\partial(\rho\langle v\rangle)}{\partial t} + \frac{1}{\phi^2}\left[\frac{\partial(\rho\langle u\rangle\langle v\rangle)}{\partial x} + \frac{\partial(\rho\langle v\rangle\langle v\rangle)}{\partial y}\right] = -\frac{\partial\langle p\rangle^f}{\partial y} + \mu_{\text{eff}}\left[\frac{\partial^2\langle v\rangle}{\partial x^2} + \frac{\partial^2\langle v\rangle}{\partial y^2}\right] - \frac{\mu}{K_y}\langle v\rangle \quad (10)$$

where $\langle u\rangle$, $\langle v\rangle$ are phase-averaged velocity components in the x and y direction, $\langle p\rangle^f$ is the intrinsic phase-averaged pressure of the fluid, ϕ is the porosity, K is the permeability of the fiber preform, and $\mu_{\text{eff}} = \frac{\mu}{\phi}$ is an effective viscosity.

The fractional volume function advection equation is

$$\frac{\partial f}{\partial t} + \frac{\langle u\rangle}{\phi}\frac{\partial f}{\partial x} + \frac{\langle v\rangle}{\phi}\frac{\partial f}{\partial y} = 0 \quad (11)$$

where velocities within the reinforcement for the new flow front determination must be corrected by a factor of ϕ^{-1}.

Boundary conditions are discussed detailedly in Ref. 12.

SIMULATION PROCEDURES

The staggered grid technology is adopted to avoid the unrealistic pressure field. The scalar variables, such as pressure, density, etc., are stored at ordinary nodal points but the velocity components on staggered grids centered around the cell faces.[13] The

TABLE I
Input Parameters of the Model[8]

Parameters	Numerical values
Inlet pressure P_0	1.9×10^4 Pa
Resin viscosity μ	0.159 Pa s
Porosity ϕ	0.5883
Permeability in flow direction K_x	4.2207×10^{-10} m^2
Permeability in transverse direction K_y	5.3977×10^{-10} m^2
Width of the edge channel d	1 mm
Air viscosity	2.1×10^{-5} Pa s

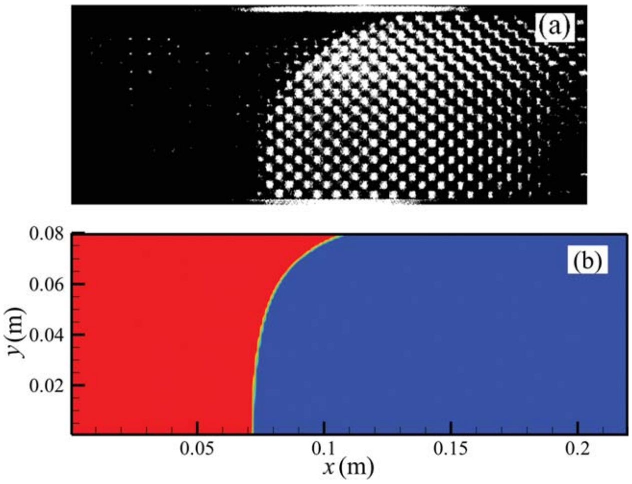

Figure 3 (a) Experimental flow fronts at t = 28.02 s for filling a preform with seven layers of fiber mats and with 1 mm of edge channel.[8] (b) Simulated flow fronts at t = 28.40 s under constant pressure injection conditions. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

finite volume method (FVM) method is used to discretize the governing equations. To minimize storage requirements, a segregated solution strategy is favored, with pressure and velocity coupled using the semi-implicit method for pressure linked equations (SIMPLE) algorithm. The piecewise linear interface construction (PLIC-VOF) method is applied to track the resin flow front.[14] The flow chart of the numerical simulation is given in Figure 2. The simulation algorithm has been validated in Refs. 12, 15 and 16.

SIMULATED RESULTS AND COMPARISON WITH EXPERIMENT

A simulation case is compared with the experimental results in Ref. 8. The size of the mold cavity in Ref. 8 is 0.22 m in length, 0.08 m in width, and 0.004 m in thickness. The main input data are listed in Table I. Their experimental results and our simulated results under constant pressure injection conditions are shown in Figure 3. A reasonable correspondence is found between the numerical results and experimental results.

TABLE II
Basic Input Parameters

Parameters	Numerical values
Inlet pressure P_0	2.0×10^4 Pa
Resin viscosity μ	0.1 Pa s
Porosity ϕ	0.81
Permeability of the fiber preform K	2×10^{-9} m^2
Width of the edge channel d	5 mm[9]
Thickness of the mold cavity h	4 mm[9]
Air viscosity	2.1×10^{-5} Pa s

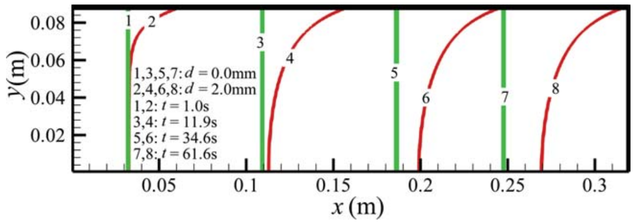

Figure 4 Evolutions of the flow fronts when considering edge effect or not. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

SIMULATION OF THE EDGE EFFECT

The mold-filling model with an edge channel is shown in Figure 1, with dimensions of 0.32 m $\times$ 0.09 m $\times$ h. The inlet pressure of the resin is considered as a constant at the mold-filling stage. The other input parameters are listed in Table II.

Results when considering edge effect or not

The evolutions of the flow fronts when considering edge effect or not are shown in Figure 4. The shape of the flow front without edge effect is straight line, but the one with edge effect is becoming semi-parabolic. It is because that the edge channel region creates a preferential flow path for the resin, which may disrupt the mold-filling. The edge flow leads to the difficulty in vent arrangement, "dry spot" formation, and other defects in the molded composite parts. It can also be seen that the filling fraction at the same filling time becomes larger with edge effect than that without edge effect under constant pressure injection conditions. Consequently, the predetermined edge channels can be used to enhance the mold-filling process.[2]

Effect of transverse permeability on flow patterns

Figure 5 gives simulation results of flow front with transverse permeability of 2×10^{-10} m^2 and 2×10^{-9} m^2. Since the pressure in the edge channels in y-direction is larger than that in the fiber preform, the resin is able to penetrate into the fiber preform through the permeable interface. The amount of

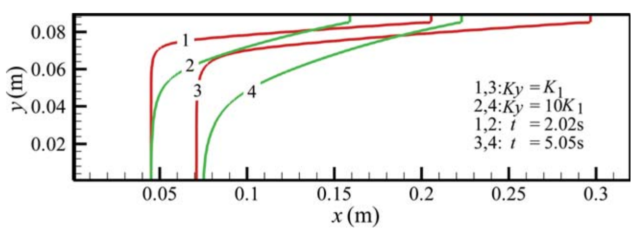

Figure 5 Flow fronts under different transverse permeabilities. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

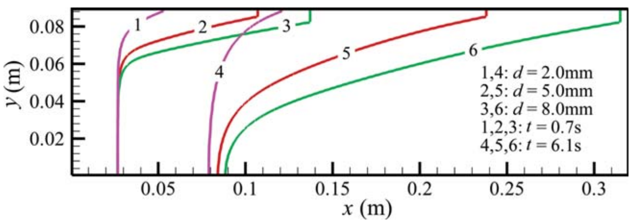

Figure 6 Effect of edge channel width on flow fronts. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

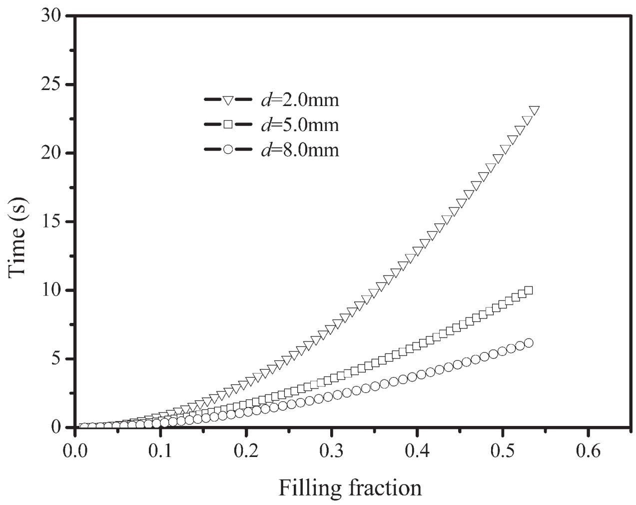

Figure 7 Filling time under different edge channel widths.

fluid that goes across the interface relates to the transverse permeability of the fiber preform.[6,8] It can be seen that the transverse flow becomes more obvious with the increase of transverse permeability.

Effect of edge channel width on flow patterns

Figure 6 shows the effect of edge channel width on flow fronts. As expected, at the same edge channel width, the edge flow always advances ahead of the bulk flow within the fiber preform, and the difference between the two flow fronts becomes larger with the filling process.

Since the increase of edge channel width leads to the enhancement of the flow in the region, the transition zone between the bulk flow and the edge flow and the flow lead-lag distance in the x-direction becomes larger with the increase of edge channel width, and the corresponding filling time arriving at the same filling fraction is a decreasing function of edge channel width, as presented in Figures 6 and 7. The simulated results are in agreement with the work by Bickerton et al.[2] Consequently, if we can supply the flow channel reasonably during the mold design, it will decrease filling times effectively, then short cycle of the production.

Effect of cavity thickness on flow patterns

Figure 8 illustrates the effect of mold cavity thickness on flow fronts. It can be seen that the transition zone between the bulk flow and the edge flow becomes larger, and the flow lead-lag distance in the x-direction becomes larger with the increase of cavity thickness. The reason is that the increase of cavity thickness leads to the decrease of viscous force in the edge channel region. The simulated results are in agreement with the work by Gupte and Advani.[4] They found that the boundary layer of the flow inside the preform was not of the order of the square root of the bulk permeability but of the order of gap thickness.

The corresponding filling time under different mold cavity thicknesses are presented in Figure 9. The lager the mold cavity thickness is, the shorter the filling time arriving at the same filling fraction are. The reason is that the increase of cavity thickness leads to the enhancement of the flow in the region.

CONCLUSIONS

A new mathematical model involving the effect of mold cavity thickness on resin flow was developed,

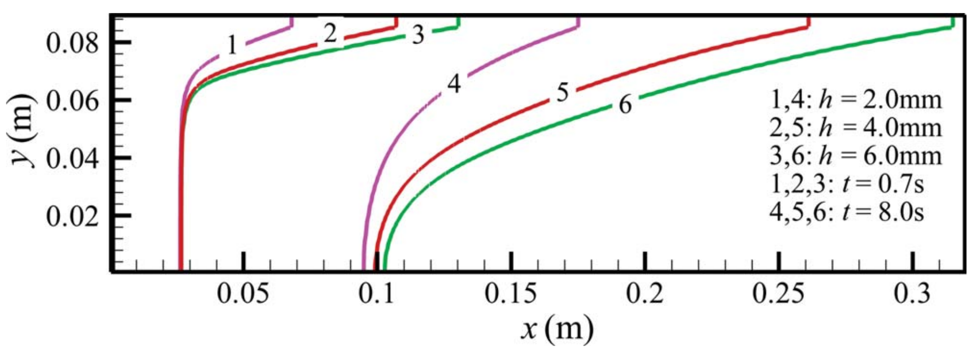

Figure 8 Effect of mold cavity thickness on flow fronts. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

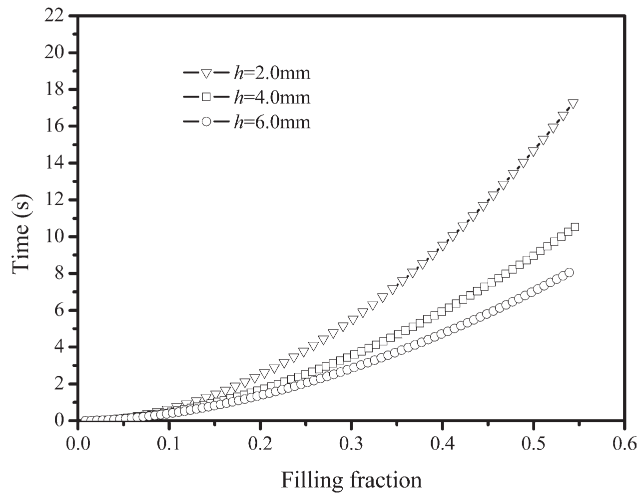

Figure 9 Filling time under different cavity thicknesses.

for simulating the resin flow with the interface between an edge channel and a porous medium, and then the edge effect in RTM processes under constant pressure injection conditions is studied. The results show that the transition zone between the bulk flow and the edge flow becomes larger, and the flow lead-lag distance in the x-direction becomes larger with the increase of edge channel width and mold cavity thickness. The transverse flow is not only affected by the transverse permeability and the edge channel width, but also by the mold cavity thickness.

It is also shown that although the edge effect may lead to the unwanted influence on resin flow, predesigned flow channels can be used to enhance the mold-filling process, for example, a shorter mold-filling time. The simulated results are in agreement with the experimental results.

To greatly deepen the study, a set of sensitivity analyzes and then some kinds of process windows should be developed in the future.

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