Effect of compressibility on flow field and fiber orientation during the filling stage of injection molding

S.C. Lee a, D.Y. Yang a,*, J. Ko b, J.R. Youn c

a Department of Mechanical Engineering, Korea Advanced Institute of Science & Technology, 373-1 Kuusong-dong, Yousung-gu, Taejon 305-701, South Korea
b Vehicle Analysis Group, Technical Center, Daewoo Motor Co. Ltd., Inchon, South Korea
c Department of Fiber and Polymer Science, Seoul National University, Seoul, South Korea

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Abstract

The anisotropy caused by the fiber orientation that is inevitably generated by the flow during the injection molding of short fiber reinforced polymers, greatly influences the dimensional accuracy, the mechanical properties and other qualities of the final product. Since the filling stage of the injection molding process plays a vital role in determining the orientation of the fiber, an accurate analysis of the flow field for the filling stage becomes a necessity. Unbalanced filling occurs when a complex or a multi-cavity mold is used, leading to the development of regions where the fiber suspension is under compression. It is impossible to make an accurate calculation of the flow field during filling within analysis assuming an incompressible fluid. In this study, a FEM/FDM hybrid scheme with consideration of compressibility was developed to calculate the flow field. At the moment of complete filling, the three-dimensional fiber orientation field was estimated by solving the equation of orientation change for the second-order orientation tensor with the fourth-order Runge-Kutta method. A mold with four cavities with different filling times was produced to compare the results of numerical analysis with experimental data. There was good agreement between the experimental and theoretical results when the compressibility of the polymer melt was considered for the numerical simulation. Also, qualitative and quantitative comparisons of fiber-orientation states for compressible and incompressible fluids were made. © 1997 Elsevier Science S.A.

Keywords: Compressibility; Fiber orientation; Flow field; Injection molding

1. Introduction

Injection molding, a highly productive manufacturing process, is capable of producing intricate net shapes without requiring finishing treatment and thus is being used widely in the electronic, automotive, aerospace and various other industries. Recently, with increasing demands for geographically complex and precision products possessing superior mechanical and chemical properties, processes such as powder injection molding, which produces complex metal or ceramic parts via the injection molding of a mixture of metal or ceramic powders and an organic binder followed by debinding and sintering, have rapidly grown. For the production of lightweight parts with good mechanical properties, the injection molding of fiber-reinforced polymeric composites is also used widely. In particular, short fiber-reinforced polymers (SFRP) not only possess the merits of continuous fiber-reinforced composites, such as high specific strength, high specific stiffness, high specific toughness, good fatigue strength and high resistance to corrosion, but they can be used for the mass-production of complex shapes with conventional polymer processing methods. Anisotropy, brought about by the complex orientation of the short fibers with the flow of the polymer melts during injection molding, leads to a deformed geometrical shape of the molded parts and negatively influences the microstructure and mechanical properties. However, with the proper prediction of flow fields and states of fiber orientation, it should be possible to control the fiber
orientation and the anisotropy, resulting in lightweight SFRP products with improved mechanical properties and reliability.

In order to properly predict the orientation of the fibers, it is necessary to be able to analyze the total flow fields composed of both shear and elongational flow: such flow fields will be utilized for the improvement of the mechanical and physical properties of SFRP and the determination of optimal die design parameters and processing conditions. Due to the numerical difficulties and considerable computational time which would be needed for a fully three-dimensional flow analysis, simulation is usually undertaken for the two-dimensional case, which involves the plane direction and the thickness direction. In general, injection molded products have a much larger characteristic length in the plane direction compared to that in the thickness direction, and thus the GHS (generalized Hele–Shaw) model is used to simulate the flow field in the plane direction [1–3], whilst a fountain flow field is used for numerical simulation in the thickness direction.

A theoretical study for the orientation of ellipsoidal particles in the flow field during flow molding was reported by Jeffery [4] in the early 1920s. Experimental and numerical methods of analysis began to emerge in the 1960s and by the 1980s Givler et al. [5] had used Jeffery's model to predict the fiber orientation in planar flows. Eduljee and Gillespie [6] derived the fiber orientation analytically for two-dimensional axisymmetric flows. Folgar and Tucker [7] proposed a diffusion-type term to take into consideration the hydrodynamic interaction between the fibers and homogeneous flow fields. Advani and Tucker [8,9] introduced the orientation tensor and the hybrid closure approximation for the transformation of higher-order tensors to lower-order tensors. Recently, numerous studies of fiber orientation using the orientation tensor have been made or are in progress [10–14].

The fiber orientation in the plane direction is highly dependent on the processing conditions, the suspension rheology and the cavity geometry. Slight differences in fiber orientation greatly influence the quality and mechanical characteristics of the final product. Among the filling, packing and cooling stages involved in the injection molding process, the filling stage plays a dominant role in determining the fiber orientation. Therefore, it is of utmost importance to be able to accurately calculate the flow field during the filling stage. In many investigations to date the polymeric melt of the filling stage has been assumed to be incompressible in order to be able to analyze the flow fields. However, with multi-cavity injection molding, all of the cavities are not filled completely at the same time. The subsequent filling of cavities results in the polymeric melt under compression, whilst in earlier-filled cavities other cavities are still in the filling stage. Numerical results modeled with incompressible GHS flow, are incapable of giving an accurate estimation of the flow field during the filling stage.

In this study, in order to make a more accurate estimation of the fiber orientation, flow field analysis was accomplished by assuming that the polymeric melt is a compressible fluid during the filling stage. In addition, a multi-cavity mold inducing, unbalanced filling, was prepared for experimental investigation. Numerical results for incompressible and compressible fluid models and experimental results verified that the compressible fluid model is more appropriate for the theoretical analysis. The fiber orientation was predicted at the instant of complete filling from flow fields obtained from flow analysis with incompressible and compressible fluid models. The second-order orientation tensors predicted for incompressible and compressible fluids were compared qualitatively and quantitatively.

### 2. Numerical modeling

In order to predict the fiber-orientation field, three governing equations, namely the continuity, momentum, and energy equations, must be solved together.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Thermal properties of the polystyrene used in the experiments and the theoretical analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$ (erg g⁻¹ °C⁻¹)</td>
<td>$18 \times 10^6$</td>
</tr>
<tr>
<td>$C_v$ (erg g⁻¹ °C⁻¹)</td>
<td>$11 \times 10^6$</td>
</tr>
<tr>
<td>$K_v$ (erg s⁻¹ cm⁻¹ °C⁻¹)</td>
<td>$17 \times 10^3$</td>
</tr>
<tr>
<td>$K_w$ (erg s⁻¹ cm⁻¹ °C⁻¹)</td>
<td>$2.15 \times 10^3$</td>
</tr>
</tbody>
</table>
with the rheological characteristics of the suspension; and the equation of orientation change for the second-order orientation tensor must be solved based on the flow field predicted. In this study, the effect of fiber orientation on the flow fields was neglected.

2.1. Formulation of the flow field

The flow field in the multi-cavity mold during injection molding is governed by a compressible, non-isothermal, non-Newtonian and transient state. Since the viscosity of the polymer melt is high, inertial effects can be neglected in the momentum equation. Viscoelastic effects are also neglected for the sake of simplification of the analysis. The governing equations for momentum balance and continuity are given as follows by making use of the compressible GHS model [15]:

\[
\frac{\partial P}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

\[
\frac{\partial}{\partial z} \left( \eta \frac{\partial u}{\partial x} \right) = \frac{\partial P}{\partial x}, \quad \frac{\partial}{\partial z} \left( \eta \frac{\partial v}{\partial y} \right) = \frac{\partial P}{\partial y}
\]

where \( x \) and \( y \) are the planar coordinates and \( z \) is the gap-wise coordinate. The energy equation for non-isothermal flow can be deduced as follows:

\[
\rho C_p(T) \left( \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + \eta \gamma^2
\]

The velocity components can be obtained by integrating Eq. (2) twice and applying the boundary conditions:

\[
u = \Lambda_x \Phi; \quad v = \Lambda_y \Phi
\]

where

Table 3

<table>
<thead>
<tr>
<th>Constants of the polystyrene for the specific volume model used for the simulation of injection molding</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_{12} ) (cm(^3) g(^{-1}))</td>
</tr>
<tr>
<td>( b_{23} ) (cm(^3) g(^{-1}) °C(^{-1}))</td>
</tr>
<tr>
<td>( b_{24} ) (cm(^3) g(^{-1}))</td>
</tr>
<tr>
<td>( b_{34} ) (cm(^3) g(^{-1}) °C(^{-1}))</td>
</tr>
<tr>
<td>( b_{41} ) (cm(^3) g(^{-1}) °C(^{-1}))</td>
</tr>
<tr>
<td>( b_{25} ) (cm(^3) g(^{-1}) °C(^{-1}))</td>
</tr>
<tr>
<td>( b_{35} ) (cm(^3) g(^{-1}) °C(^{-1}))</td>
</tr>
<tr>
<td>( b_{45} ) (cm(^3) g(^{-1}) °C(^{-1}))</td>
</tr>
<tr>
<td>( b_1 ) (°C)</td>
</tr>
<tr>
<td>( b_0 ) (°C cm(^2) dyne(^{-1}))</td>
</tr>
</tbody>
</table>

Fig. 2. Results of the short-shot experiments in the case of slow filling (case 1: \( Q = 3.4 \text{ cm}^3 \text{s}^{-1} \)).

\[ A_x \equiv -\frac{\partial P}{\partial x}, \quad A_y \equiv -\frac{\partial P}{\partial y}, \text{ and } \Phi \equiv \int_{0}^{z} \frac{z}{\eta} \, dz. \]

The mass flow rate per unit length in the \( x \) and \( y \) directions is given as follows:

\[
\dot{m}_x = 2 \int_{0}^{h} \rho u \, dz = 2S \Lambda_x \quad \dot{m}_y = 2 \int_{0}^{h} \rho v \, dz = 2S \Lambda_y
\]

The fluidity factor \( S \) is defined as follows:

\[
S = \int_{0}^{h} \rho \Phi \, dz
\]

By integrating Eq. (1) in the thickness direction and applying Eq. (5), the governing equation for the pressure field is obtained as follows:

\[
\frac{\partial}{\partial z} \left( S \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial y} \left( S \frac{\partial P}{\partial y} \right) = \frac{\partial}{\partial t} \int_{0}^{h} \rho \, dz
\]

In order to improve numerical stability, the compressibility term of the right-hand side of Eq. (7) is decomposed into two terms that represent the influence of

Fig. 3. Predicted melt-front advancements assuming compressible flow in the case of slow filling (case 1: \( Q = 3.4 \text{ cm}^3 \text{s}^{-1} \)).
temperature and pressure on density change [15]. The governing equation for the pressure field finally becomes:

\[ G \frac{\partial P}{\partial t} - \frac{\partial}{\partial x} \left( \delta \frac{\partial P}{\partial x} \right) - \frac{\partial}{\partial y} \left( \delta \frac{\partial P}{\partial y} \right) = - F \]  

(8)

where:

\[ G = \int_0^z \left( \frac{\partial \rho_1}{\partial \rho} \frac{\partial \rho_2}{\partial \rho} \right) dz + \int_z^h \left( \frac{\partial \rho_1}{\partial \rho} \frac{\partial \rho_2}{\partial \rho} \right) dz \]

\[ F = \int_0^z \left( \frac{\partial \rho_1}{\partial \rho} \frac{\partial T}{\partial \rho} \right) \frac{\partial T}{\partial t} dz + \int_z^h \left( \frac{\partial \rho_2}{\partial \rho} \frac{\partial T}{\partial \rho} \right) \frac{\partial T}{\partial t} dz + \left( \rho_1 - \rho_2 \right) \chi_{T(z)} \frac{\partial \chi}{\partial t} \]  

(9)

(10)

in which \( \chi \) is the \( z \) coordinate of the solid-liquid interface and subscripts 1 and 2 denote the liquid phase and the solid phase, respectively. Tait's experimental Eq. [16] was employed for the \( p-v-T \) model of the amorphous polymers.

\[ v(T, P) = v_0(T) \left\{ 1 - C \ln \left( 1 + \frac{P}{B(T)} \right) \right\} + v_1(T, P) \]  

(11)

where \( C = 0.0894 \). The above equation of state is capable of describing both the liquid and solid regions by the changing of the constants in \( v_0(T) \) and \( B(T) \):

\[ v_0(T) = \begin{cases} \frac{b_{13} + b_{21} T}{b_{14} + b_{25} T} & \text{if } T > T_i \\ \frac{b_{13} + b_{25} T}{b_{14} + b_{25} T} & \text{if } T < T_i \end{cases} \]

(12)

\[ B(T) = \begin{cases} b_{31} \exp(-b_{41} T) & \text{if } T > T_i \\ b_{34} \exp(-b_{42} T) & \text{if } T < T_i \end{cases} \]

(13)

where \( T \equiv T - b_5 \). In addition, the transition temperature is assumed to be a linear function of pressure as follows:

\[ T_i(P) = b_5 + b_6 P \]  

(14)

The modified Cross model was selected as follows to represent the viscosity (\( \eta \)) of the suspension as follows:

\[ \eta = \frac{\eta_0}{1 + \eta_0 \left( \frac{\tau^*}{\tau} \right)^n} \]  

(15)

where:

\[ \eta_0 = B \exp \left[ \frac{T_b}{T} \right] \exp \left( \frac{\beta P}{T} \right) \]  

(16)

Constant \( n \) is the power-law exponent and \( B, \tau^*, T_b, \) and \( \beta \) are material constants.

Using the weighted residual method, a finite-element equation for the nodal pressure can be derived for Eq. (8) as follows:

\[ \frac{A^{(0)}}{3} \sum_{i=1}^{3} \frac{E_{iN} P_i - P^{(i)}}{\Delta t} + \frac{A^{(0)}}{3} \sum_{i=1}^{3} D^{(0)} P_i = - \frac{A^{(0)}}{3} P^{(0)} \]  

(17)

In this study, following the global assembly of all elements, the substitution method was used to calculate the pressure at all nodes, whilst the temperature distribution in the thickness direction was determined by solving the energy equation with finite-difference methods.

2.2. Formulation of the orientation field

In order to predict the orientation field, the relationship between the deformation field and the orientation function is required. The orientation tensor, orientation parameters, and orientation distribution function are frequently used orientation functions. The second-order orientation tensor not only minimizes the problem of computational complexity, which is a big disadvantage of the orientation distribution functions, but also has properties of symmetry, normality and compactness which make it suitable to be used as an orientation function. The second-order orientation tensor is defined as the integral in all directions of the dyadic product of the position vector \( \vec{F} \) and the probability distribution function \( \phi(\vec{F}) \):

\[ a_{ij} = \int P_i P_j \phi(\vec{F}) d\vec{P} \]  

(18)

The equation of orientation change for the second-order orientation tensor proposed by Advani and Tucker [8,9] was employed for the analysis:

\[ \frac{\partial a_{ij}}{\partial t} = \frac{\partial a_{ij}}{\partial t} = \frac{1}{2} \left( \omega_{ik} a_{kj} - a_{ik} \omega_{kj} \right) + \frac{1}{2} \left( \dot{\gamma}_{ik} a_{kj} + a_{ik} \dot{\gamma}_{kj} - 2 \dot{\gamma}_{ik} \omega_{kj} \right) + 2 C \dot{\gamma}_{im} (\delta_{ij} - 3 a_{ij}) \]  

(19)
where $\lambda$ is a parameter dependent on the shape of the fiber particle, being defined as $\lambda = (r_e^2 - 1)/(r_e^2 + 1)$. For short fibers, which usually possess large equivalent aspect ratios $r_e$, its value is equal to unity $C_1$ as a dimensionless interaction coefficient introduced by Folgar and Tucker [7], representing the degree of interaction between short fibers, in this study its value being chosen as 0.001.

In order to approximate the fourth-order tensor in Eq. (19), the hybrid closure approximation, $\tilde{a}_{ijkl}$ which considers both the linear closure, $\tilde{a}_{ijkl}$ and quadratic closure, $\tilde{a}_{ijkl}$ was implemented as follows [8]:

$$\tilde{a}_{ijkl} = a_{ijkl} - (1 - F)\tilde{a}_{ijkl} + F\tilde{a}_{ijkl}$$

The scalar measure of orientation $F$, determined by the degree of orientation, is related to the orientation tensor by the following:

$$F = 1 - 4 \det a_2$$

In this study, in order to predict the three-dimensional fiber orientation field at the instant of complete filling, the fourth-order Runge–Kutta method was employed to solve Eq. (19) at all layers through the thickness direction at each finite element centroid.

3. Results and discussion

In order to verify the validity of the results of the compressible flow analysis during the filling stage, experiments were carried out on an injection molding machine (Jaco III-H-3) with a clamping force of 50 tons, an injection capacity of 3.5 oz (85 g) and a maximum injection pressure of 170 MPa. Unbalanced filling was induced with the design of a four-cavity mold with different filling times for each cavity. More specifically, two cavities of identical rectangular shapes had gates located at different points (cavity 1, cavity 2), and the other two cavities were channel-shaped (cavity 3) and L-shaped (cavity 4). The pressure in the cavities during filling was measured using a pressure transducer (Kistler Piezo sensor 6157A) and compared to the numerical results. Fig. 1 shows the mesh used in the FEM analysis, the dimensions of the cavities and the location of the pressure transducers. The thickness of all the cavities is 2 mm and the radius of the runner is 3 mm. Experiments and numerical analyses were undertaken with such processing conditions as a coolant temperature of 60°C, a melt temperature of 40°C and injection flow rates of 3.4 (case 1) and 13.4 cm$^3$ s$^{-1}$ (case 2). Table I shows the thermal properties of the amorphous polymer PS (polystyrene) used in the experiments and numerical calculations, whilst Tables 2 and 3 show the viscosity model constants and the specific volume model constants, respectively.

Fig. 2 shows the results of the short-shot experiments at time intervals until complete filling of the mold is reached with an injection flow rate of 3.4 cm$^3$ s$^{-1}$ (case 1). It can be seen in Fig. 3, which shows numerical results with the same injecting conditions, that the advancement of the melt fronts and the order of filling (cavity 1, cavity 2, cavity 3, cavity 4) agree well with the experimental results, the estimated filling times being 2.05 and 0.513 s for case 1 and 2, respectively. As can be seen in Fig. 2, these estimated filling times concurred well with the experimental results. Fig. 4 shows a comparison between the experimental and the numerical results of the differences in pressure measured at the runner and two other pressure transducer locations in the end-gated rectangular cavity (cavity 2) with processing conditions given by case 1. The pressure difference $\Delta P_{ij}$ corresponds to the pressure drop across the gate of the cavity 2, which is denoted by $P_1 - P_2$ in the
Fig. 6. Predicted fiber orientation for slow filling (case 1) at the layer \( z/h = 0.4 \): (a) incompressible case; (b) compressible case.

Fig. 7. Predicted fiber orientation for slow filling (case 1) at the layer \( z/h = 0.8 \): (a) incompressible case; (b) compressible case.
Fig. 8. Predicted fiber orientation for fast filling (case 2) at the layer \( z/h = 0.1 \); (a) incompressible case; (b) compressible case.

In Figs. 5–7 predicted fiber orientations at three different layers in the thickness direction upon complete filling are shown in the case of slow filling (case 1) for incompressible fluid and compressible fluid whilst Figs. 8–10 show the predicted fiber orientation for case 2 where the flow rate is large and the filling time is small. The initial fiber orientation at the flow entrance was taken randomly in order to achieve isotropy. Fig. 11 displays the velocity distribution in the flow direction with respect to the \( z \) coordinates obtained from the compressible and incompressible calculations at the centroids of finite elements A, B, and C under case 1 before the cavity is filled (\( t = 1.06 \) s). It can be seen that the compressible and incompressible calculations produce identical results when complete filling does not occur and that the velocity component is zero for layers \( 9 \) (\( z/h = 0.8 \)) and above due to solidification. It can also be noted that between layer \( 1 \) (\( z/h = 0 \)), the central layer and layer \( 3 \) (\( z/h = 0.2 \)) elongational flow is dominant, between layers \( 3 \) and \( 7 \) (\( z/h = 0.6 \)) elongational and shear flow co-exist, and for layers \( 7 \) and above shear flow is dominant. According to the state of short fiber orientation in the thickness plane, the domain in the thickness plane can be classified into three regions: core, transition, and shell regions. As can be seen in Figs. 5 and 8, the fiber is aligned normal to the flow direction due to elongational flow at the central region in the thickness direction (layer 2), which is the core region. Figs. 7 and 10 show that due to shear flow, fibers close to the mold surface (layer 9) are aligned in the direction of flow, i.e. at the shell region. Figs. 6 and 9 show that between the core and shell regions (layer 5), the fibers are aligned normal to the flow direction of flow due to elongational flow near to the gate and are aligned in the direction of flow due to shear flow near to the mold surface, i.e. at the transition region. Comparison of Figs. 6 and 9 indicates that the fiber orientation in the transition region changes with different
processing conditions. It can be seen that due to the shear flow more fibers are oriented in the direction of flow for case 1 than for case 2, because the injection flow rate is slower in case 1 than in case 2. Such tendencies, as can be seen in Fig. 12, occur because larger solid layers are formed near to the cold mold surface for case 1 where the temperature in the thickness direction is low. As the solid layer becomes thicker, the velocity gradient in the thickness direction becomes sharper, resulting in a more shear-dominant flow which causes higher fiber orientation in the direction of flow. Fig. 13 shows that, unlike the incompressible calculation, the compressible fluid model results in fluid movement in the cavity after cavity 2 is completely filled. It can be seen that the velocity is very small in the completely filled cavities and that in cavity 2 the velocity component at B, the gate region, is larger than that at C, the end region. Therefore, due to compressibility effects, the density will increase faster and the fiber orientation will change by a larger amount, near to the gate.

For quantitative examination of compressibility effects on the fiber orientation, Fig. 14 shows the predicted component ($a_{11}$) of the orientation tensor at nodes A and B, which are points near to the gates of cavities 1 and 2, respectively. The figure shows the existence of critical values of orientation in the cavity 1, i.e. the fiber orientation no longer changes upon complete filling. For the multi-cavity mold and case 1 used in the present investigation, the critical degree of orientation in the core region due to elongational flow was 0.1 and that in the shear-flow dominant shell region was 0.96. At node A of cavity 1 (the side-gated rectangular cavity), the velocity components caused by the compressibility effects, shown in Figs. 13 and 14, have

![Fig. 11. Predicted axial velocity distribution as a function of normalized z coordinates at finite elements A and B after 1.06 s for slow filling (case 1).](image)

![Fig. 12. Predicted temperature profile as a function of normalized L coordinates at the centroid of elements A, B and C at the moment of complete filling in the case of fast filling (filling time = 0.51 s) and slow filling (filling time = 2.05 s).](image)
almost no effect on the fiber orientation field. It can be seen that as cavity 1 becomes completely filled and the flow field fully developed, the fiber-orientation field converges to the critical degree of orientation. As shown in Figs. 13 and 14, at complete filling of node B of cavity 2 (the end-gated rectangular cavity), the additional velocity component induced by compressibility effect acts to decrease the degree of orientation in the flow direction in the core and transition regions. This implies, as can be verified in Figs. 5 and 6, that the fiber orientation realigns normal to the direction of flow near to the gate region of cavity 2. In the shear-flow dominant shell region, no effect of compressibility can be found, since the solid layer is not affected by the compressible flow and the fiber orientation has reached critical values.

Fig. 14. Predicted variation of $a_{11}$ components of the orientation tensor with respect to the normalized $z$ coordinates at nodes A and B in the case of slow filling (case 1) after complete filling.

Fig. 13. Predicted axial velocity distribution with respect to the normalized $z$ coordinates at elements A, B and C after 1.62 s for slow filling (case 1).

Fig. 15 compares the difference between the maximum eigenvalues of the orientation tensors predicted for incompressible and compressible fluid models at layer 5 ($z/h = 0.4$). In case 1 a maximum difference of 29% in fiber orientation is obtained at the gate region of cavity 2, whilst the maximum difference is 21.5% for case 2. It can be seen in Fig. 16, which plots the difference between the maximum eigenvalues predicted for compressible and incompressible fluids at each node where the difference between the two maximum eigenvalues of the fiber orientation is the largest, that changes in fiber orientation due to compressibility effects were more prominent in the transition region than in the core region. Compressibility had more significant effects on the fiber-orientation field for case 1, where the filling time was longer than that for case 2.
A critical degree of orientation exists, where the orientation no longer changes. For the multi-cavity mold used in the present investigation, the critical degree of orientation in the core region was 0.1, and 0.96 in the shell region, for cavity 1 in the case of slow filling.

Compressibility does not have any effect on the orientation field for the side-gated rectangular cavity, where the fully developed flow leads to the critical degree of orientation.

Compressibility has the most significant effect on the orientation field for the gate region of the end-gated rectangular cavity. When the compressibility is considered the degree of orientation in the flow direction decreased in the core and transition regions whilst there was no change in the shell region.

Changes in fiber orientation caused by compressibility occur prominently in the transition region when the flow rate is low.

Fig. 16. Predicted variation of the difference between the maximum eigenvalues with respect to the normalized z coordinates where the difference is maximum for each case.

4. Conclusions

The following conclusions are made from the analysis of the flow field and fiber orientation with the compressible fluid model during the filling stage.

1. The compressibility of the polymer melt does not impose any significant influence on the flow field when any cavity has not been completely filled.

2. The effect of the compressibility can be seen in the flow field in a completely filled cavity when the other cavities are still in the process of filling.

3. The numerical results of the compressible fluid model agree well with experimental results.

4. Layers defined parallel to the thickness plane can be classified into the core, transition, and shell regions, depending upon the states of fibers orientation.

5. When the filling times were long because of slow injection flow rates, the low-temperature distribution in the thickness direction induces an expansion of the shell region.

References