Structural Resin Transfer Moulding with Compression Process

Hiroyuki Hamada
Faculty of Textile Science, Kyoto Institute of Technology
Matsugasaki, Sakyo-ku, Kyoto, Japan

and

Naoto Ikegawa
Production Engineering Research Laboratory, Matsushita Electric Works, Ltd.
Kadoma, Osaka, Japan

ABSTRACT

Gap closure rate significantly affected on void formation behaviour in structural resin transfer moulding (SRTM) with compression process, by which low void content moulded parts could be realized. Effects of the gap closure rate on void formation behaviour were examined by numerical analysis using finite element method (FEM). According to a concept of homogenization method, equivalent viscosity was introduced as an index of flow resistance expressing presence of reinforcement. Assuming that the porosity has a characteristic of anisotropy, anisotropic equivalent viscosity could also be represented. These enabled to calculate fluid motion in the system with porous medium using FEM. The difference of void formation behaviour due to the gap closure rate was determined by a balance of flow property between the in-plane and the out-of-plane directions. Moreover, effect of reinforcement construction pattern on flow behaviour was calculated by that analysis model was divide into 4 layers with different equivalent viscosity. Arranging anisotropic layers with small equivalent viscosity ratio on the bottom side and with high equivalent viscosity ratio on the top side, flow behaviour through the thickness direction was unified.

INTRODUCTION

A well-known problem with manufacturing methods for polymer matrix composites such as SRTM (structural resin transfer moulding), SMC (sheet moulding compound) moulding, filament winding, and the autoclave process is that the finished part contains voids. For some applications a modest void content in the composite is acceptable, while for other applications where high strength, high water resistance, or a fine surface finish is required, it is of utmost importance that the void content is low. Hence, there have been a number of research works focused on this problem. It was reported that the presence of voids in graphite/epoxy unidirectional composites resulted in significant reduction of the transverse and shear modulus, and the compressive strength (1-2). For reaction injection moulding (RIM) of urethane, it was reported that the voids were caused by entrapment of air during mould filling (3).

It is assumed that void formation mechanism for SRTM is different from that in these processes, because the impregnation behaviour for SRTM can be regarded as replacement of air in the reinforcement with the resin. Replacement of air with the resin would be necessary for removal of the voids. In other words, how to flow the air with the resin and how to replace the air with the resin are very important to improve an impregnation property. Understanding of the void flow behaviour leads to improvement of the impregnation property. There are many research works related to the analysis of void formation mechanism by Elmendorp et al. (4), Damani et al. (5), Patel et al. (6), and Wang et al. (7), whereas methodological approaches for removal of the voids is very little studied. Hamada et al. have investigated the problem how to remove the voids based on the concept that the voids are driven out with the resin flow (8). However, this technique has a limitation in the case of high fibre content. For example, increase of fibre content was particularly prevented from the problems of formation of dry spots or high void region. Therefore we proposed a new fabrication method which can realize low void content moulded parts (9). This method could be improved driving out voids compared with conventional SRTM method. The gap closure rate significantly affected on void formation behaviour.

In this study, effect of the gap closure rate on void formation behaviour in SRTM with compression process was investigated by numerical analysis using a finite element method (FEM). This numerical analysis was enabled by derivation of equations governing fluid motion in the system with porous medium such as fibrous reinforcement. According to a concept of homogenization method, an equivalent viscosity was introduced as an index of flow resistance. Assuming that a porosity has a characteristic of anisotropy, anisotropic equivalent viscosity could be represented. Flow analysis was performed introducing anisotropic equivalent viscosity. Moreover, effect of reinforcement construction on flow behaviour was examined by that analysis model was divide into 4 layers with different equivalent viscosity.

SRTM WITH COMPRESSION PROCESS

Figure 1 shows schematic diagram of the gap height and pressure as a function of time. After the reinforcement is set into the mould cavity, the upper half of mold moves downward. When the gap height (ΔH) reaches a given value, the downward motion of the upper mold stops and the gap is kept at a constant. After injection of resin is complete, the upper mold moves downward at a constant velocity (V). Accordingly, resin flow is caused by the squeezing motion, and the mold cavity is finally filled with resin. The pressure rises as the gap height decreases, and predetermined pressure (P) is applied to the molded parts when the gap reaches zero, and then the mold filling ends.

THEORETICAL

Assuming that the fluid is incompressible, the flow is steady, and gravitational and inertial forces are negligible, the equations of motion and the continuity equation reduce to

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} \qquad (1)$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (3)$$

In order to analyze the flow behaviour in the system with porous medium, accurate modeling anisotropic reinforcement is not realistic. Flow resistance of the fluid is represented by a viscosity. However, the flow resistance increases according to the presence of reinforcement. The flow resistance can not be expressed by viscosity of resin only. Therefore an equivalent viscosity as flow resistance considering the presence of reinforcement was introduced.

The equivalent viscosity is expressed by the product of viscosity dependent on permeability and viscosity dependent on shear rate.

$$\bar{\mu} = \mu(\dot{\gamma}, K) = \mu_{\dot{\gamma}}(\dot{\gamma}) \cdot \mu_K(K) \qquad (4)$$

The viscosity dependent on permeability $\mu_K(K)$ was calculated by modeling tubular flow. The permeability can be expressed by using a porosity (ε), tube diameter (d) and dimensionless constant (c) (10).

$$K = \varepsilon c d^2 \qquad (5)$$

Here, the porosity is given by dimensions of rectangular shape section with a tube as shown in **figure 2.**

$$\varepsilon = \frac{\pi\, d^2}{4 l_a l_b} \qquad (6)$$

From equations (5) and (6), the permeability is given as a function of the tube diameter.

$$K(d) = \frac{\pi c d^4}{4 l_a l_b} \qquad (7)$$

The tube diameter equivalent to the area of this section becomes $\sqrt{\frac{4 l_a l_b}{\pi}}$. The range of the permeability is

$$0 \le K \le \frac{4 l_a l_b\, c}{\pi} \qquad (8)$$

Taking K_0 as a maximum tube diameter, K_0 indicates the permeability in the system without reinforcement. When $\mu_K(K)$ is defined as the ratio of K_0 to K(d), it is expressed as reciprocal of square of the porosity.

$$\mu_K(K) = \frac{K_0}{K(d)} = \left(\frac{4 l_a l_b}{\pi\, d^2}\right)^2 = \frac{1}{\varepsilon^2} \qquad (9)$$

Substituting equation (9) into equation (4), the equivalent viscosity becomes

$$\bar{\mu} = \mu(\dot{\gamma}, K) = \frac{\mu_{\dot{\gamma}}(\dot{\gamma})}{\varepsilon^2} \qquad (10)$$

The equivalent viscosity increases with decrease of the porosity.

Moreover, taking ε_x and ε_y as the porosities in the x and y directions on the assumption that the porosity is anisotropic, anisotropic equivalent viscosities are given as

$$\bar{\mu}_x = \mu\,(\dot{\gamma}, K_x) = \frac{\mu_{\dot{\gamma}}(\dot{\gamma})}{{\varepsilon_x}^2} \qquad (11)$$

$$\bar{\mu}_y = \mu\,(\dot{\gamma},K_y) = \frac{\mu_{\dot{\gamma}}(\dot{\gamma})}{\varepsilon_y{}^2} \tag{12}$$

The equations governing the behaviour of a fluid motion can be derived as follows.

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \bar{\mu}_x\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{13}$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \bar{\mu}_y\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{14}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{15}$$

Based on equations (13)-(15), flow behaviour in the system with porous medium can be calculated by numerical analysis method such as FEM.

NUMERICAL ANALYSIS

It was seen that the gap closure rate affects the void formation behaviour significantly (9). When the gap closure rate was high, the voids were expelled towards the end of cavity. Whereas voids distributed in a circle centring the gate on the top surface of the molded parts in the case of small gap closure rate. To confirm this difference of void formation by the gap closure rate, short-shot moldings were fabricated by changing a stopping position (H1) of the upper half of mould during the mould closing after the injection at ΔH=12 mm, and the void behaviour was estimated. Comparison of the void formation behaviour between V=5 and 100 mm/min is schematically shown in **figure 3.** The flow direction is from left to right in figure. In the case of H1=12 mm, the resin only ran through the reinforcement and the porous part was formed on the upper side through the thickness direction. The lower side through the thickness direction was filled with the resin. In the filling part a thickness near the gate differed from that near the cavity end. The thickness of the filling part changed sharply around the distance from the gate of 100 mm. When the upper mould moved downward to the position of H1=5 mm at any gap closure rate, the air in the cavity was driven out toward the end of cavity by the resin flow and high void region was restricted to be formed at the front part ahead. However, in the case of V=5 mm/min the voids were located in the boundary region between the porous and the filling parts where the thickness of the filling part changed.

A flow analysis using finite element method was performed to analyze the effect of the gap closure rate on the void formation. The filling state of resin in the cross section including the gate when injected at the position of H1=12 mm was modeled as shown in **figure 4**. The region surrounded with a dashed line represents an outline of the filling part. A thickness under the porous part is 6 mm and the other region has 3 mm thickness. The gap closure rate was given as constant initial velocity to nodes on the top of the thick part. An anisotropy of flow property between the in-plane and the out-of-plane directions was expressed introducing anisotropic equivalent viscosity. The equivalent viscosity ratio ($\bar{\mu}_x/\bar{\mu}_z$) between the in-plane and the out-of-plane directions was changed in the range from 0.1 to 10. **Figure 5** shows the flow velocity distributions near the part with change in thickness. In the case that the equivalent viscosity ratio was 1.0, the flow toward the top from the bottom was formed near where the thickness sharply. (*Case (a)*) When the equivalent viscosity ratio was more than 1.0, a tendency of the flow in Case (a) became intensive. (*Case (b)*) This result indicates that existence of the flow toward the top from the bottom leads to the formation of voids by an entrapment of air. On the other hand, when the viscosity ratio was 0.1, the flow from the bottom disappeared and flow through the thickness direction tended to be uniform. (*Case (c)*) The flow toward the top from the bottom was unlikely with decrease of the equivalent viscosity ratio, that is, with increase of the flow property in the in-plane direction. The gap closure rate affected an in-plane permeability, which would be higher as the gap closure rate become larger (11). Therefore, these results suggest that higher gap closure rate would bring improvement of flow property in the in-plane direction according to increase of the in-plane permeability, and consequently formation of the voids due to entrapment was unlikely. Moreover, it was clear that the phenomenon whether the voids were formed or not was determined by a balance of the flow property between the in-plane and the out-of-plane directions.

Of particular important is how to make the flow behaviour through the thickness direction uniform during the mould filling so as not to form the voids on the top surface. One way to fabricate the moulded parts without the voids might be to change a surface density or a configuration of reinforcements through the thickness direction. In order to examine an effect of reinforcement construction on flow behaviour through the thickness direction, the analysis model was divided into 4 layers that possess different equivalent viscosity and numerical analysis was performed. The equivalent viscosity ratio of each layer are shown in **table 1**. **Figure 6** shows an effect of insert position of anisotropic layer on the velocity distributions when single anisotropic layer with small equivalent viscosity ratio was incorporated into isotropic layers. Velocity distribution in *Case (d)* was similar to that in Case (a). As the insert position shifted from 1st to 3rd layer, the flow toward the top from bottom slightly decreased. Velocity of 3rd and 4th layers increased in *Case (f)*. To place anisotropic layer with small equivalent viscosity ratio on the bottom side is effective to make the flow behaviour uniform. **Figure 7** shows an velocity distributions using two anisotropic layers. In the case that two anisotropic layers with small equivalent viscosity ratio were placed on the top side, the flow behaviour had a strong resemblance to Case (a) or Case (d). (*Case (g)*) When two anisotropic layers with *small* equivalent viscosity ratio and those with *high* equivalent viscosity ratio were arranged in order from the top surface, there were vectors being at almost right angles with x direction and the velocity on the top side was large compared with Case (g). (*Case (h)*) In the contrary case of lay-up pattern to Case (h), the right-angled vectors disappeared by arranging anisotropic layers with *small* equivalent viscosity ratio on the bottom side. Moreover, the velocity on the top side decreased and flow behaviour through the thickness direction was larger unified than Case (c), due to arranging anisotropic layers with *high* equivalent viscosity ratio on the top side (*Case (i)*).

CONCLUSION

Gap closure rate significantly affected on void formation behaviour in SRTM with compression process. Effects of the gap closure rate on void formation behaviour were investigated by numerical analysis using FEM. Flow resistance of the fluid is represented by a viscosity. However, the flow resistance in the system with porous medium, such as fibrous reinforcement in SRTM, can not be expressed by resin viscosity only, because that it increases due to presence of reinforcement. Therefore the equivalent viscosity was introduced as the flow resistance considering presence of reinforcement. Assuming that the porosity has a characteristic of anisotropy, anisotropic equivalent viscosity could also be represented. Accordingly, it was possible to calculate fluid motion in the system with porous medium using FEM. Analysis results indicated that difference of void formation behaviour due to the gap closure rate was determined by a balance of flow property between the in-plane and the out-of-plane directions. In the case of slower gap closure rate, existence of the flow dominated in the out-of-plane direction leads to entrapment of air and results in the formation of voids. Moreover, effect of reinforcement construction pattern on flow behaviour was calculated by that analysis model was divide into 4 layers with different equivalent viscosity. Arranging anisotropic layers with small equivalent viscosity ratio on the bottom side and with high equivalent viscosity ratio on the top side, flow behaviour through the thickness direction was unified.

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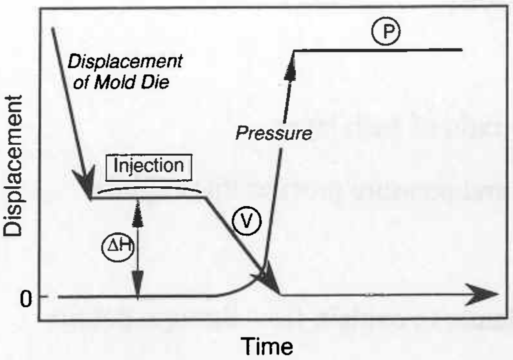


Figure 1 Schematic diagram of gap height and pressure profiles that explains moulding variables.

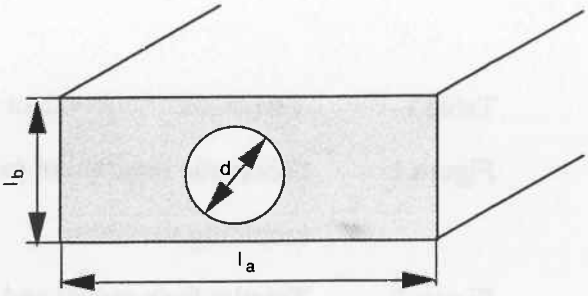
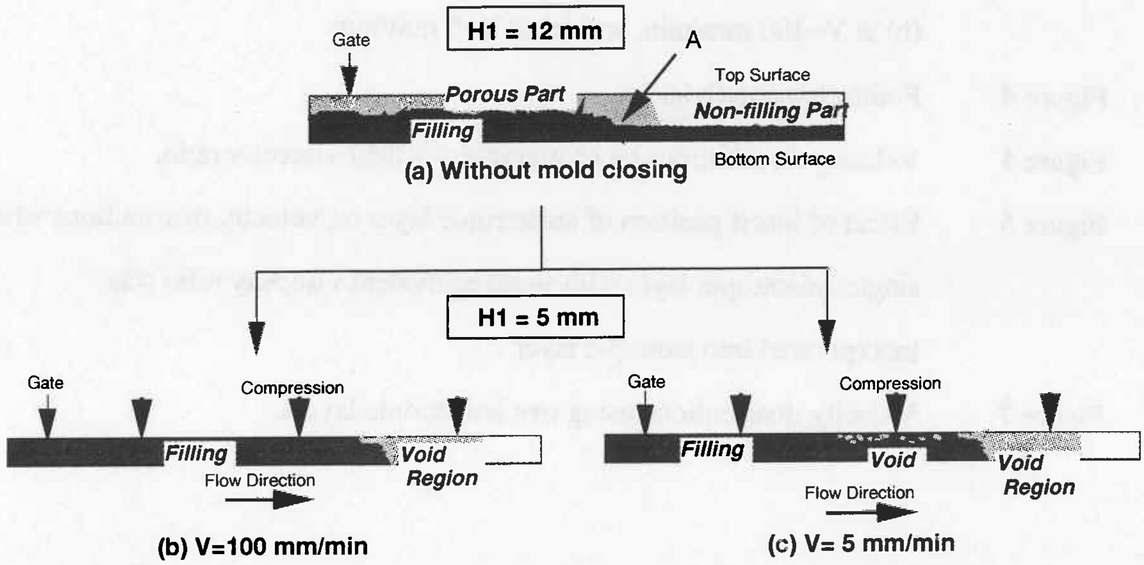


Figure 2 Tubular flow model and nomenclature to explain flow through porous medium.



(a) Without mold closing

(b) V=100 mm/min

(c) V= 5 mm/min

Figure 3 Comparison of void formation behavior between V=5 and 100 mm/min when the upper mould moved downward from H1=12 mm to H1=5 mm; (a) without mould closing (H1=12 mm), with mould closing (b) at V=100 mm/min, and (c) at V=5 mm/min.

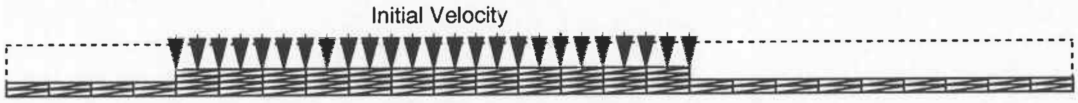
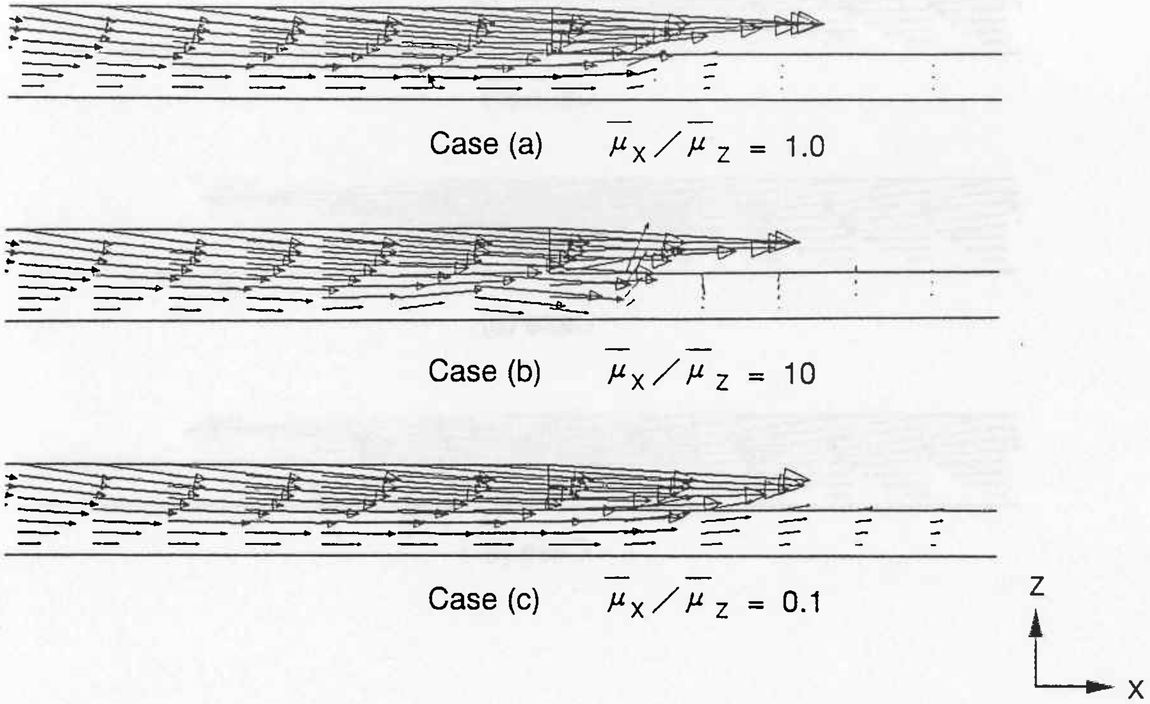


Figure 4 Finite element divisions.


Case (a) $\overline{\mu}_X / \overline{\mu}_Z = 1.0$

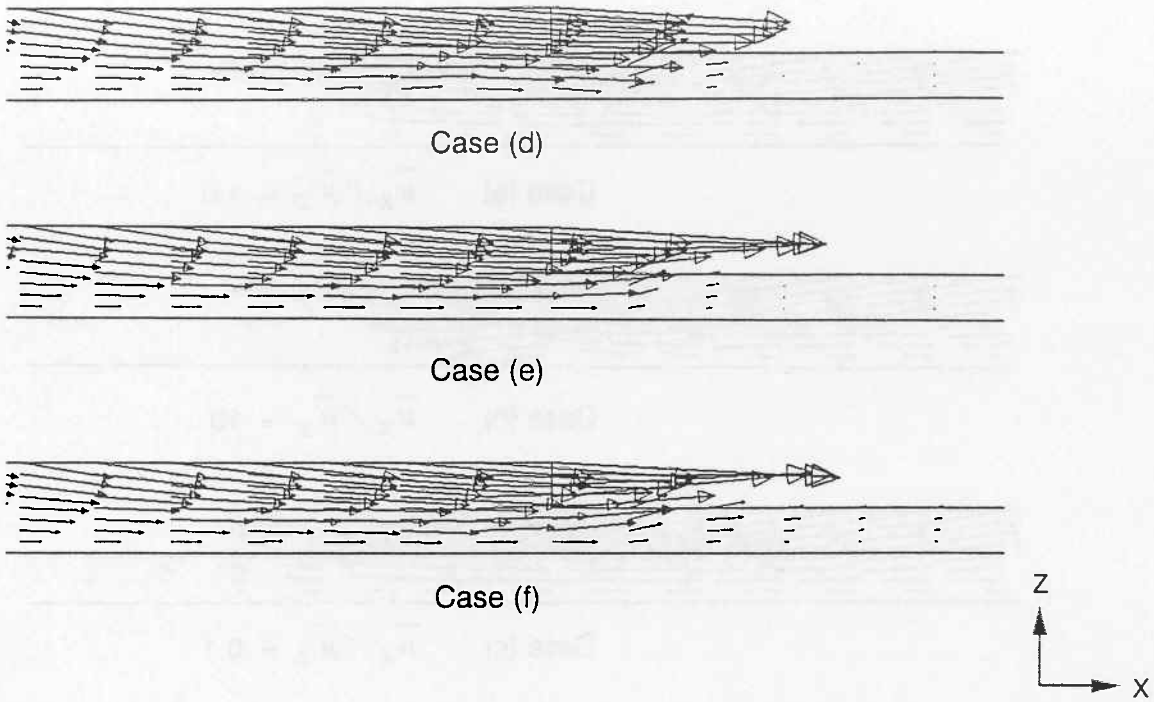
Case (b) $\overline{\mu}_X / \overline{\mu}_Z = 10$

Case (c) $\overline{\mu}_X / \overline{\mu}_Z = 0.1$

Figure 5 Velocity distributions by changing equivalent viscosity ratio.

Table 1 Variation of equivalent viscosity ratio of each layer.

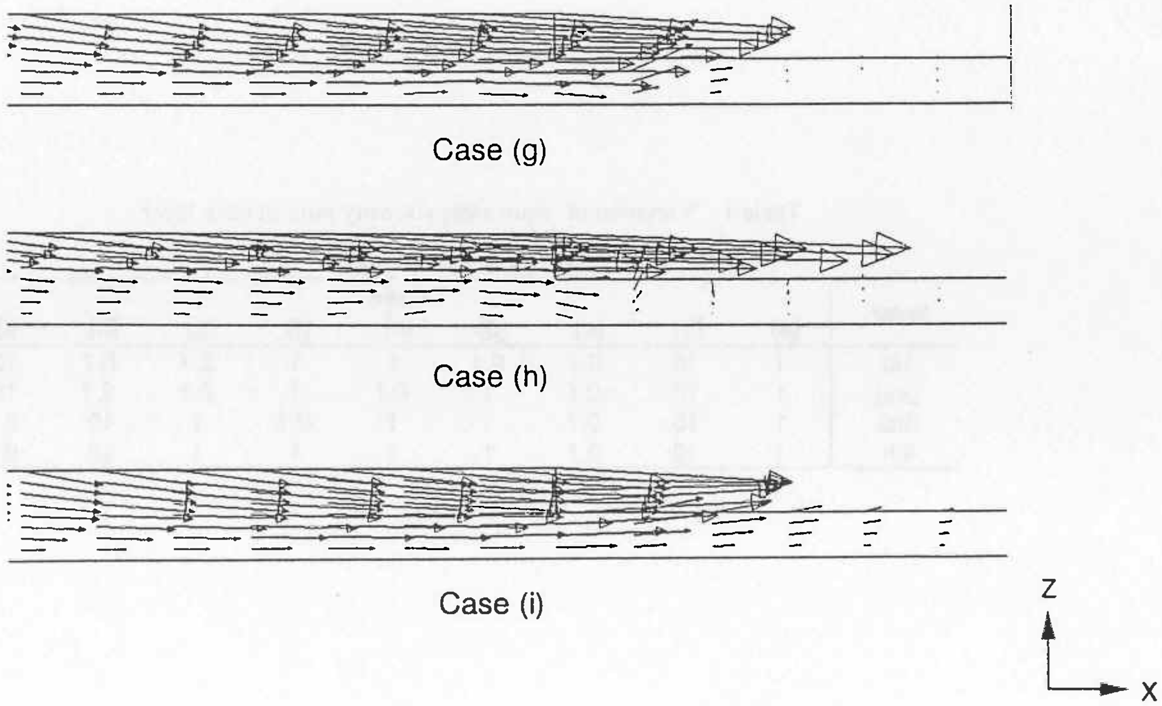
layer	Case (a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
1st.	1	10	0.1	0.1	1	1	0.1	0.1	10
2nd.	1	10	0.1	1	0.1	1	0.1	0.1	10
3rd.	1	10	0.1	1	1	0.1	1	10	0.1
4th.	1	10	0.1	1	1	1	1	10	0.1


Case (d)

Case (e)

Case (f)

Figure 6 Effect of insert position of anisotropic layer on the velocity distributions when single anisotropic layer with small equivalent viscosity ratio was incorporated into isotropic layers.


Case (g)

Case (h)

Case (i)

Figure 7 Velocity distributions using two anisotropic layers.