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Short Communication

Effect of shim configuration on internal die flows for non-Newtonian coating liquids in slot coating process

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In this study, a strategy for designing optimal shim configuration inside a slot die is suggested to assure the uniform coating flow distribution of various non-Newtonian shear-thinning liquids at the die exit in a slot coating system. Flow patterns of non-Newtonian liquids inside the slot die, via three-dimensional computations, have been compared using various shim geometries which can adjust the flow region in a slot manifold. The rather non-uniform (parabolic) velocity distributions of shear-thinning liquids at the die exit under the basic shim condition could be effectively flattened by the modification of shim geometry without the change of die manifold structure. Dimensions of hybrid shims for controlling flow features at edge and center regions within slit channel are positively tuned, according to the shear-thinning level of coating liquids.

Keywords: slot die, shim configuration, internal die design, non-Newtonian liquid, slot coating

1. Introduction

Slot coating process has been mainly applied in many industries manufacturing high functionality films, secondary batteries, fuel/solar cells, adhesive tapes, and so on due to its useful and beneficial advantages. The coating thickness can be pre-determined from the mass balance of flow rate and web speed, taking into account one of pre-metered coating processes (Cohen and Gutoff, 1992; Kistler and Schweizer, 1997). Also, very thin coating operation is possible under high web speed conditions, by controlling the vacuum box which is helpful to stabilize a coating bead region (*i.e.*, a liquid space between upstream/downstream die lips, moving web, and free surfaces of a coating liquid at upstream and downstream die regions) (Higgins and Scriven, 1980; Gates, 1999; Tanwar *et al.*, 2007; Lee *et al.*, 2011a). Regarding only theoretical aspects on this process, there have been a variety of reports in examining coating flow characteristics, focusing on the coating bead region. Fuller theories and simulations have been steadily explored to interpret coating bead dynamics (Carvalho and Kheshgi, 2000; Romero *et al.*, 2006; Nam *et al.*, 2009; Bhamidipati *et al.*, 2011; Lee *et al.*, 2014). Also, simplified viscocapillary models have been usefully applied to decide operability coting windows for various Newtonian and non-Newtonian coating liquids in relatively low capillary number regimes by changing the flow rate and web speed without vacuum pressure or the vacuum pressure and web speed under the constant coating thickness (Tsuda, 2009; Lee *et al.*, 2011a; Koh *et al.*, 2012; Ahn *et al.*, 2015).

Further, flow features inside the slot die should be carefully accounted for the optimal internal die design because aforementioned flow dynamics in coating bead region were actually based on the uniform distribution of coating flows at the die exit. Manifold structure inside the die formed by chamber-and-slit sections and shim, as shown in Fig. 1, significantly affects the internal die flow. Note that the shim, which is inserted between upstream and downstream dies, can decide the size and shape of slit channel. That is, for the uniform velocity distribution of various coating liquids at the die exit, internal manifold structure has been designed by revamping chamber-and-slit or shim shapes inside the die. Pearson (1964) investigated the effect of chamber shape on the internal flow in the slit channel. McKelvey and Ito (1971) and Matsubara (1979) suggested simplified models to decide the internal die geometries for melt flow of power-law fluids in the extrusion systems. Lee and Liu (1989) examined two-dimensional (2-D) flow inside the die with non-circular chamber. Sartor (1990) elaborately summarized the method to design internal slot die for the uniform coating. Yuan (1995) and Ruschak and Weinstein (1997) mentioned the role of second chamber in controlling the internal flow. Recently, Lee *et al.* (2011b) introduced the optimal die design for non-Newtonian coating liquids by modifying chamber and slit regions.

However, a slot die with specialized chamber and slit structures, which provides the coating uniformity for a selected coating liquid, cannot always guarantees the similar level of uniformity for other rheologically different liquids. It is not desirable to replace each time very expen-

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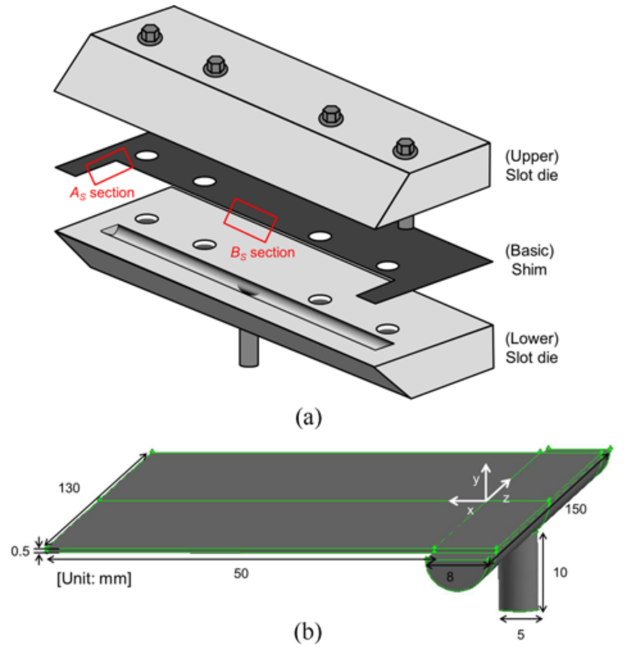


Fig. 1. (Color online) (a) Schematic structure of slot die and (b) internal manifold by the basic shim of (a).

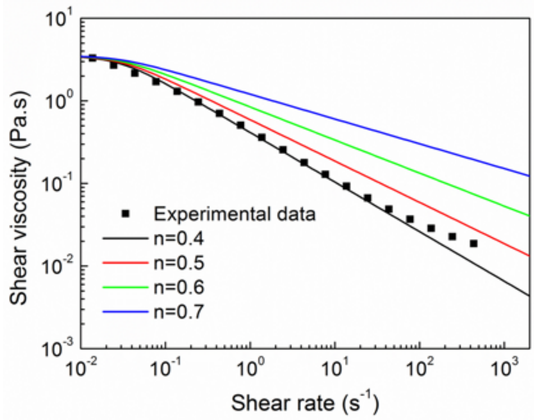


Fig. 2. (Color online) Shear viscosity data of shear-thinning coating liquids with different power-law indices used for simulations (Carreau model parameters: η_0 = 3.5 Pa·s, η_∞ = 0.003 Pa·s, λ = 35 s).

sive slot dies independently optimized for various non-Newtonian liquids. One idea is that the shim modification without changing the manifold structure of a given slot die can effectively minimize the non-uniformity of coating flow inside the die. There are few reports to emphasize the role of shim on the internal die flow, except some patents (Byun, 2012; Jeon *et al.*, 2015; Park *et al.*, 2015), introducing the conceptual manifold or shim designs for industrial applications.

In this study, the effect of shim configuration on the flow characteristics inside the slot die has been investigated for various shear-thinning coating liquids via three-dimensional calculations. The illustrative strategy for optimal shim design is suggested to show the minimization of the non-uniform velocity distributions of coating liquids at the die exit by changing shim geometry.

2. Simulations for Internal Die Flows

Three-dimensional (3-D) computations (Fluent) are employed to theoretically examine steady-state internal die flows. The governing equations for non-Newtonian liquids are as follows,

Equation of continuity: $\underline{\nabla}\cdot\underline{v} = 0$; (1)

Equation of motion: $\rho(\underline{v}\cdot\underline{\nabla}\underline{v}) = -\underline{\nabla}P + \underline{\nabla}\cdot\underline{\underline{\tau}} + \rho\underline{g}$; (2)

Constitutive equation (with Carreau fluid model):

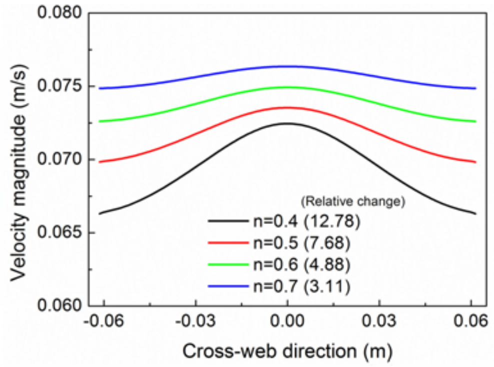
$$\underline{\underline{\tau}} = \eta(|\dot{\gamma}|)\underline{\underline{\dot{\gamma}}},\ \eta = \eta_\infty + (\eta_0 - \eta_\infty)(1 + (|\dot{\gamma}|\lambda)^2)^{(n-1)/2} \quad (3)$$

where $\underline{v}$ denotes the velocity vector, ρ is the liquid density (= 1,126 kg/m^3), P is the pressure, $\underline{g}$ is the gravitational acceleration vector, $\underline{\underline{\tau}}$ is the stress tensor, η_0 is the zero-shear-rate viscosity (= 3.5 Pa·s), η_∞ is the infinite viscosity (= 0.003 Pa·s), $\underline{\underline{\dot{\gamma}}}$ is the rate of deformation tensor, λ is the material time constant (= 35 s), n is the power-law index, respectively. Above equations are implicitly solved on the basis of finite volume method (FVM) with appropriate boundary conditions inside the die (Lee *et al.*, 2011a; Han *et al.*, 2014). As boundary conditions, constant flow rate at the feed inlet (= 3.64 × 10^{-6} m^3/s), no slip at the solid walls, and pressure outlet conditions are adopted in the computations. Dimensions of manifold structure inside the die determined by the basic shim are designated in Fig. 1b. Note that A_s and B_s sections of the shim in Fig. 1a were mainly modified with respect to the properties of coating liquids. It is verified that the number of meshes inside the die chosen for simulations (around 160,000) is sufficient to guarantee accurate numerical solutions.

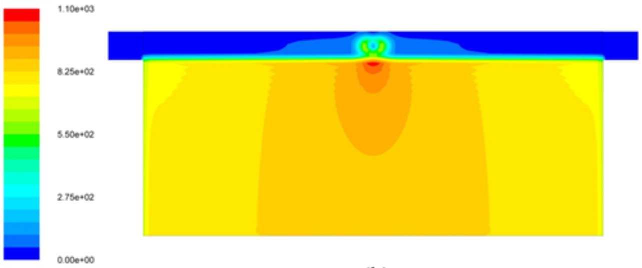
Fig. 2 shows viscosity data of shear-thinning coating liquids with different power-law indices, n, used for simulations. A coating liquid with $n = 0.4$ is chosen as a reference liquid in which a small amount of xanthan gum polymer (Sigma-Aldrich) of 1,200 ppm is added to a mixture of glycerin and water of 50:50 wt.%. Carreau model parameters except power-law index were obtained by fitting experimental shear viscosity data.

3. Results and Discussion

Fig. 3a shows the velocity profiles along the center line at the die exit for different shear-thinning liquids, when the basic shim is applied. Also, the relative velocity deviation, which is the difference between maximum and min-

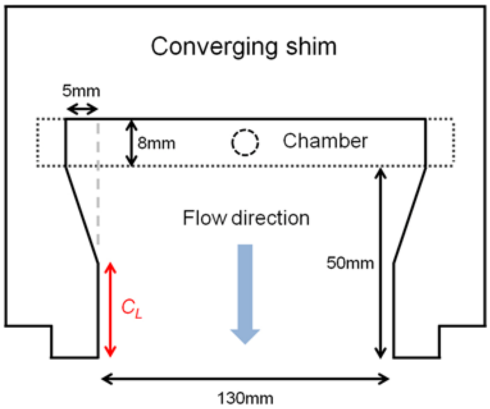


(a)

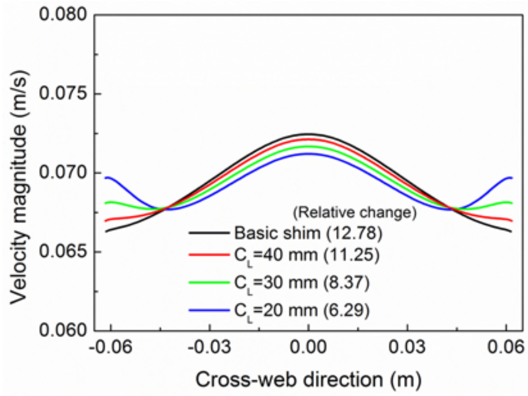


(b)

Fig. 3. (Color online) (a) Effect of power-law index (n) on velocity distribution at die exit (a value in parenthesis denotes the relative velocity change) and (b) wall shear-rate contour for a liquid with n = 0.4, when the basic shim is applied.



(a)



(b)

Fig. 4. (Color online) (a) Shim structure modified in converging A_s section of the basic shim and (b) the effect of downstream length (C_L) on velocity distribution at die exit for the liquid with n = 0.4 (a value in parenthesis denotes the relative velocity change).

imum velocities with respect to the average velocity, at the die exit was presented in the figure to grasp non-uniformity level for each liquid. As the power-law index (n) decreases (*i.e.*, increasing shear-thinning effect), the velocity profile becomes more parabolic, inducing larger coating non-uniformity. Typically, the shear rate at the slit wall is decreasing from the middle to the edge regions inside the slit channel, developing the non-uniform velocity distribution along the width (see Fig. 3b for the liquid with n = 0.4). In this case, the flow control inside the slit regime must be suitably carried out by modifying the shim structure to increase velocity at the edge and to decrease velocity at the center, respectively. We tried to modify shim shape, in particular A_s and B_s sections of the basic shim, to obtain the desirable velocity distribution inside the slit channel.

The effect of converging slit structure around A_s section on the velocity distribution at the die exit is presented in Fig. 4 for the liquid with n = 0.4. As the converging length around A_s section increases (*i.e.*, decreasing length C_L in Fig. 4a), the velocity at the edge side considerably increases. The increase of a converging part at slit edges generally creates the more wavy velocity distribution along the width, although the coating uniformity is likely to be improved from the results of relative velocity changes within the limited conditions in Fig. 4. For the further modification of the shim, the length C_L of 40 mm, not showing wavy profiles yet, was selected here.

To practically lower the velocity at the center region within the slit, the upstream flow near the slit entrance needs to be adjusted by changing the B_s section of the basic shim. Fig. 5 displays the effect of protruding triangular shape in the B_s section on the velocity distribution at the die exit for the liquid with n = 0.4. Note that the protruding shape in the B_s part can control the flow around the slit entrance region and the triangular shape shown in Fig. 5a is found to be more favorable among the simple protruding forms, *i.e.*, in comparison with the semi-circular and rectangular ones with the same area, producing the smooth streamlines near the slit entrance region and well-distributed velocity in the slit channel. In Fig. 5a, the height of triangle shape (T_L) was changed under its constant width. There is little change of velocity distribution at the die exit when the height of triangle shape is not so much larger than the chamber diameter, because the liquid can enter towards the slit entrance region without structural restriction. As its height gets gradually increases larger than the chamber diameter, the velocity level at the

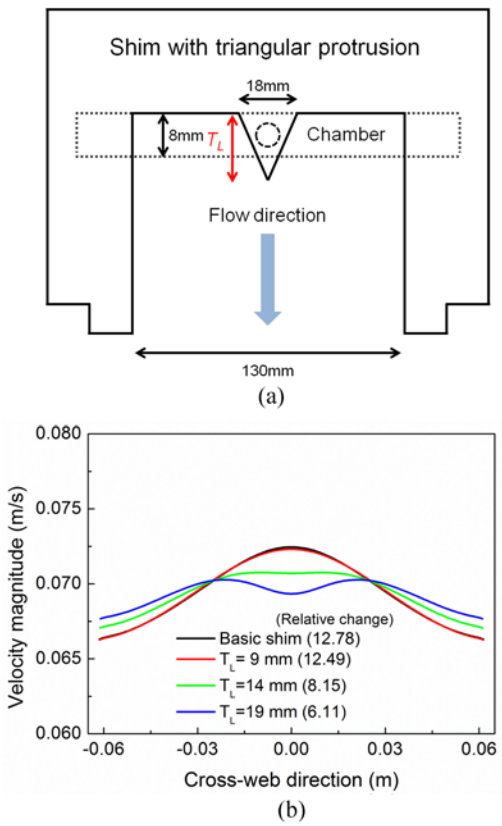


Fig. 5. (Color online) (a) Shim structure modified in B_s section of the basic shim and (b) the effect of downstream length (T_L) on velocity distribution at die exit for the liquid with $n = 0.4$ (a value in parenthesis denotes the relative velocity change).

die exit is remarkably reduced. However, further increase of T_L leads to the severe wavy velocity distribution along the width. Under the given geometric and operating conditions in this study, the triangular height of 14 mm was chosen for the further modification of the shim.

Considering the roles of both A_s and B_s regimes of the shim in regulating the flow features of non-Newtonian liquids within the slit channel, one exemplary strategy to nicely minimize the non-uniformity of velocity profiles under somewhat limited conditions was suggested in the next. For instance, in the case that a coating liquid shows non-uniform parabolic velocity distribution at the die exit, as in this study, we have tried to improve the internal die flow to certify its uniformity at the die exit by reasonably modifying shim configuration such as the suitable converged A_s geometry for increasing velocity level at both edges and the appropriate protruded B_s geometry for slightly decreasing velocity level at the center. Under the constant downstream slit length ($C_L = 40$ mm) behind converging A_s section and the constant height of protruding triangular section ($T_L = 14$ mm), desirable hybrid shim shapes for the uniform coating of various shear-thinning liquids were tuned by finding optimal converging width

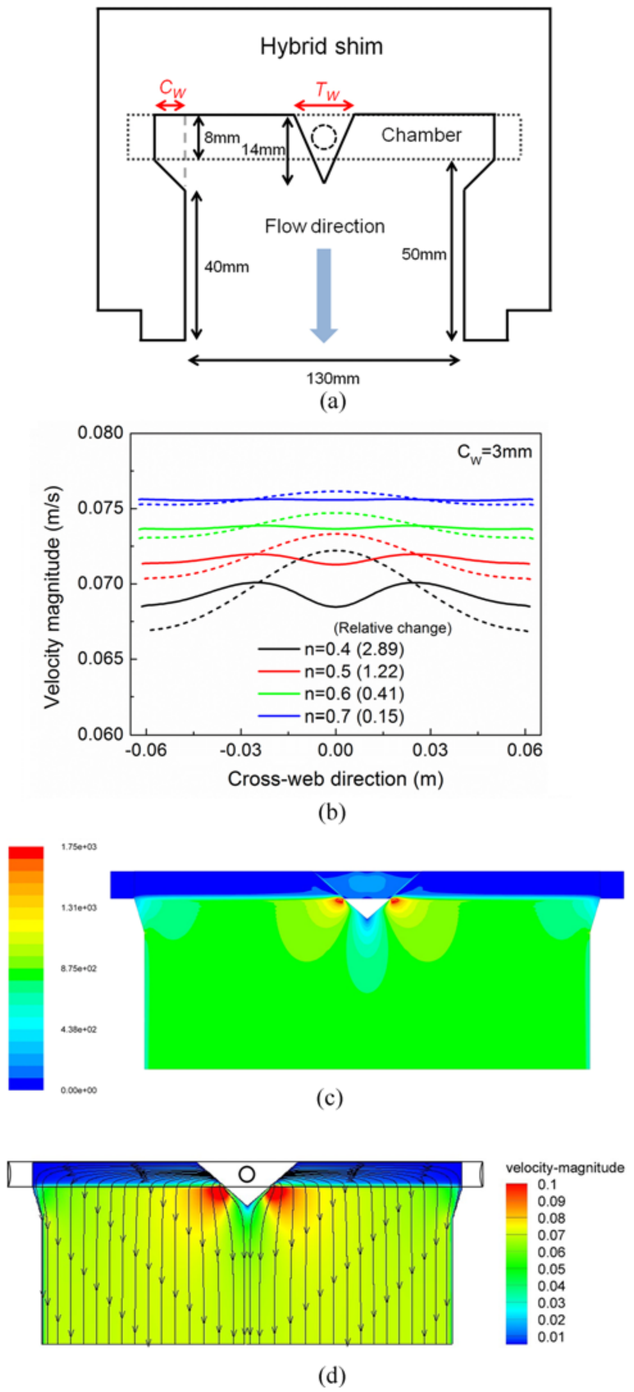


Fig. 6. (Color online) (a) Shim structure modified in both A_s and B_s sections of the basic shim and (b) the comparison of velocity distributions at die exit for various shear-thinning liquids when the basic (dash lines) and hybrid (solid lines) shims are applied and (c) wall shear-rate contours and (d) velocity contours with streamlines for the liquid with $n = 0.4$, when the hybrid shim is applied.

(C_W) and triangle width (T_W) (Fig. 6a). It is worthwhile mentioning here that there exist of course better combinations of geometrical variables to design the optimal

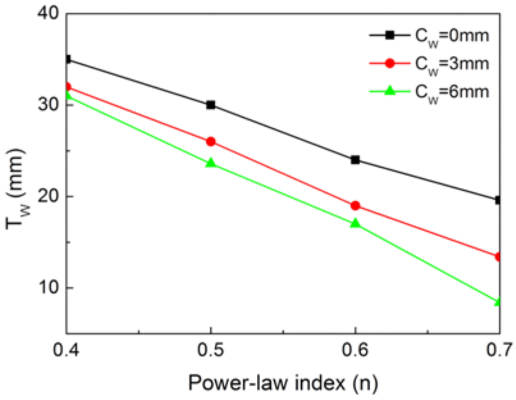


Fig. 7. (Color online) Optimal dimensions for triangle width (T_W) in the hybrid shim for various converging widths (C_W) and shear-thinning liquids.

shim for non-Newtonian coating flows. Fig. 6b shows the comparison of velocity distributions along the width at the die exit for non-Newtonian liquids when the optimized shim in the case of $C_W = 3$ mm (solid lines) and the basic shim (dash-lines, same as Fig. 3a) were applied. As clearly seen in this figure, relative velocity deviations by using the hybrid shim were positively reduced in comparison with those by using the basic shim for coating liquids considered in this study. Also, as seen in Fig. 6c, wall shear-rate distribution within the slit channel region for the liquid with $n = 0.4$ is more improved, when the hybrid shim is implemented between upstream and downstream dies, in comparison with Fig. 3b by the use of basic shim. Additionally, velocity contours together with streamlines under the hybrid shim operation are depicted in Fig. 6d. In Fig. 7, overall optimal dimensions of triangle width (T_W) for various converging widths (C_W) and coating liquids with different power-law indices are listed, including data in Fig. 6b. It is evident that the non-uniformity of velocity profiles at the die exit could be notably improved in the slot coating systems for rheologically different coating liquids, employing the methodology of hybrid shim design suggested in this study.

4. Conclusion

One possible strategy to optimally design shim inserted between upstream and downstream slot dies is suggested in this study for ensuring the coating uniformity of non-Newtonian liquids in slot coating process. From 3-D simulations, internal die flows for various shear-thinning liquids were compared by changing shim structure. The hybrid shim modified in the edge and center sections of the basic shim can be satisfactorily devised to minimize non-uniform parabolic velocity distribution at the die exit, considering the shear-thinning level of a coating liquid. This approach for optimal shim design can be directly applied in slot coating processes with diverse purposes, as one of internal die designs.

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