Simulation of the Polymeric Fluid Flow in the Feed Distributor of Melt Blowing Process

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Received 22 September 2005; accepted 18 October 2005
DOI 10.1002/app.23515
Published online in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The polymeric fluid flow in the feed distributor of melt blowing process is simulated using three-dimensional finite element method. The numerical results are experimentally verified quantitatively and qualitatively using laser Doppler velocimetry and particle image velocimetry respectively. The effects of the distributor's geometric parameters on the uniformity of the transverse flow distribution are investigated. As the manifold angle increases, the flow distribution curve appears to transform gradually from a "hill" shape to a "bone" shape. The uniformity of flow distribution at distributor outlet, especially the fluctuation at the central part, will be improved by increasing the land height. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 1570–1574, 2006

Key words: simulations; processing; rheology; melt blowing; coat hanger distributor

INTRODUCTION

Melt blowing is a one-step process in which high-velocity air blows a molten thermoplastic resin from an extruder die tip onto a conveyor or take-up screen to form a fine fibrous and self-bonding web. It has become an important textile industrial technique because of its ability to produce the fabrics with microfiber structure, which are well suited for filtration media, surgical wraps and gowns, feminine hygiene products, thermal insulators, battery separators, and oil sorbents. Most research on the melt blowing process are focused on the air drawing of the polymer,[1,2] the performance of the jet slot dies,[3–5] the fiber movement,[6] and the prediction of the fiber diameter.[7,8] However, seldom research is conducted to deal with the feed distributor although its design is of significant importance.[9] In the melt blowing process, the polymer is passed through an extruder where the molten material is forced through a feed distributor. To produce meltblown nonwoven fabrics with a uniform microfiber structure, the distributor must be well designed to distribute the polymer melt uniformly across its width. The distributor in a melt blowing die is more critical than in a film or sheeting die, as the melt blowing die usually has no mechanical adjustments to compensate for variations in polymer flow across the die width. Presently, the coat hanger type distributor is widely used in the melt blowing die and its design is done mainly empirically.

Sun et al. analyzed the non-Newtonian flow in the coat hanger die of the melt blowing process by using the popular one-dimensional lubrication model.[9] In this method, the slot and manifolds are generally modeled using formulae developed for isothermal flow in parallel plates and in circular tube respectively. These formulae are coupled to provide expressions for pressure drop along all possible flow paths. One or more criteria are then imposed to define desirable performance characteristics, the most basic one being equal pressure drop along all flow paths, leading to uniform melt distribution across the die. It is true that the resulting design equations are analytical and simple in form. However, due to the excessive assumptions and the complexity of the non-Newtonian fluid flow in it, the coat hanger die designed through one-dimensional lubrication theory cannot produce uniform flow distribution at die outlet. To know the nature of the polymer flow in it and therefore provide a more effective design method, we adopt the finite element method to simulate the polymeric fluid flow in the coat hanger feed distributor.

NUMERICAL FORMULATION AND EXPERIMENTAL VERIFICATION

Assuming the polymer fluid flow in the melt blowing distributor is an isothermal steady flow of an incom-

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Contract grant sponsor: National Natural Science Foundation of China; contract grant numbers: 10402009 and 50506007.
Contract grant sponsor: Shanghai Dawning Program; contract grant number: 05SG37.

Journal of Applied Polymer Science, Vol. 101, 1570–1574 (2006)

pressible power-law fluid, the governing equations are written as follows:

$$-\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ik}}{\partial x_k} + \rho g = \rho v_k \frac{\partial v_i}{\partial x_k} \quad (1)$$

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (2)$$

$$\tau_{ik} = \eta(I_2)\left(\frac{\partial v_i}{\partial x_k} + \frac{\partial v_k}{\partial x_i}\right) \quad (3)$$

$$\eta(I_2) = m I_2^{n-1} \quad (4)$$

$$I_2 = \frac{1}{2}\sum_i \sum_j \dot{\gamma}_{ij}\dot{\gamma}_{ji} \quad (5)$$

where p is pressure, x is Cartesian coordinate, τ is stress, ρ is fluid density, g is acceleration of gravity, v is velocity, η is viscosity, I_2 is magnitude of strain rate, $\dot{\gamma}$ is strain rate, m is consistence index, and n is power-law index. The subscripts represent the components of the vector or the tensor (i, j = 1, 2, 3).

Equation (1) is the momentum balance equation, in which the inertia and gravity terms are considered. In most numerical simulation of polymeric fluid flow, it is assumed that the flow is slow enough for the inertia term to be neglected. However, in many cases such as the extrusion of wax or polymer solution with low viscosity, the inertia and gravity are quite important. Equation (2) is the mass conservation equation with incompressible constraint. Equation (3) is the constitutive equation, in which the viscosity function is described with power-law equation (4). The governing equations assume that the temperature is fixed and constant. Pittman gave a careful study on the adaptability of isothermal assumption to the polymer flow in slit die and pointed out that isothermal assumption was valid under the most processing conditions.[10]

Depicting the variation in pressure by shape functions of one order lower than those for defining the velocity distribution, the velocity is approximated with quadratic polynomial and the pressure is approximated with linear polynomial. A brick isoparametric element is adopted. The velocity is interpolated at the 20 nodes, while the pressure is interpolated only at the eight corner nodes.

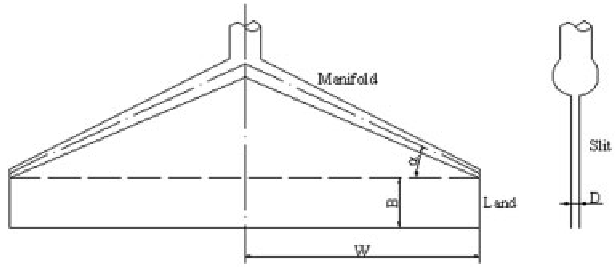

Figure 1 The schematic diagram of coat hanger distributor.

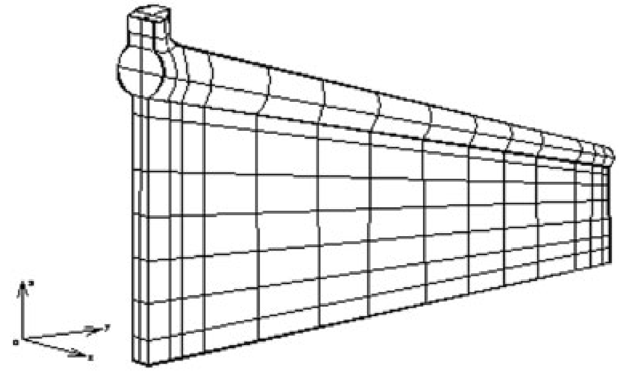

Figure 2 The finite element meshes layout.

In Figure 1 is shown the schematic diagram of coat hanger distributor. In simulation only one half of the coat hanger distributor is considered because of its symmetry. The finite element meshes layout of the coat hanger distributor is shown in Figure 2.

By discretizing the governing equations according to the Galerkin method, we obtained the following form of the finite element equation:

$$\begin{bmatrix} A(v_i) & A_p \\ A_p^T & 0 \end{bmatrix} \begin{bmatrix} v_i \\ p \end{bmatrix} = \begin{bmatrix} R \\ 0 \end{bmatrix} \quad (6)$$

where v_i is the velocity vector with three components v_1, v_2, and v_3 along x, y, and z direction respectively, $A(v_i)$ and A_p are the matrix elements including the velocity and pressure respectively, R is the right-hand nonzero vector, and T represents the transpose of matrix.

The element matrix equation is then assembled over all elements and the boundary conditions are imposed over the final system. The boundary conditions are no-slip conditions at the wall for the three velocity components. At the x–z symmetry plane, the y-component velocity is zero and zero surface tractions in the x and z directions are imposed. The axial velocity component is uniform at the inlet and the pressure is atmospheric pressure at the outlet. The final system is a set of nonlinear equations, the nonlinearity of which arises from the material law and the inertia term. It is possible in general to use Newton's method to deal with this nonlinear system. However, it is often difficult to obtain a converging sequence. A simple iterative procedure is used in the paper. The first step computes the Newtonian creeping flow solution, and iteration proceeds from this solution. The viscosity and the inertia term appearing in $A(v_i)$ are calculated in terms of the old nodal velocity components.

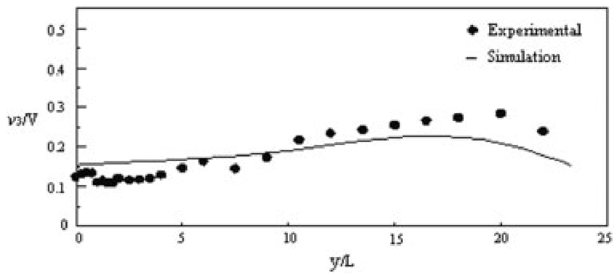

Figure 3 Comparison of the LDV experimental data with the simulation results.

The applicability of the numerical scheme was experimentally verified quantitatively and qualitatively using laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) respectively. In the experiment, the 2% CMC/water solution was prepared as the test fluid. Its viscosity was measured using the RV-II coaxial rotary viscosimeter. The experimental data were fitted by regression to determine the power law parameters $n = 0.673$ and $m = 2.992$ Pa s^n. In the LDV experiment, the velocities of the 25 points at the die outlet were measured. By comparing the experimental data with the simulation results, it can be seen from Figure 3 that both results show a same tendency: the vertical velocity v_3 gradually increases along the y direction, reaches a peak near the far end of the die, and then begins to decrease.

To obtain the instantaneous information of the entire flow field, the PIV technique was used to display the flow pattern at the central plane of the coat hanger distributor. By comparing Figure 4 with Figure 5, we can see that the theoretical analysis predicts the polymeric liquid flow in the slot of the die very well. The fluid entering the slot flows with a bigger velocity component along the y direction. Just before arriving at the outlet, the fluid begins to flow in the direction normal to the exit plane. Due to the poor transparency of the manifold, the flow pattern in it was not obtained. However, it can be seen from the theoretical results that the fluid in the manifold does not flow along its axial direction completely as assumed in one-dimensional analysis.

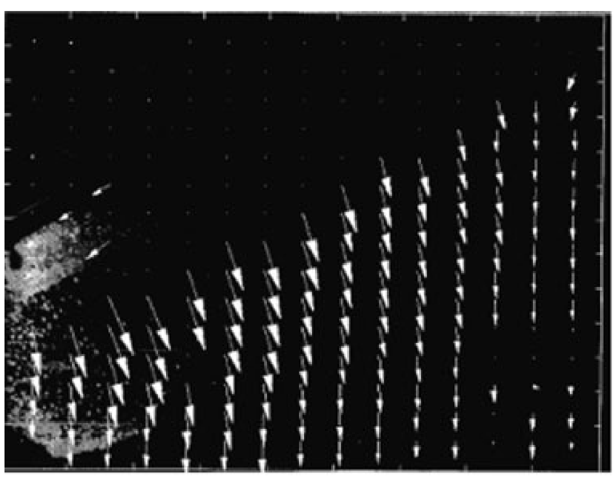

Figure 4 The flow pattern at the central plane of the distributor from PIV.

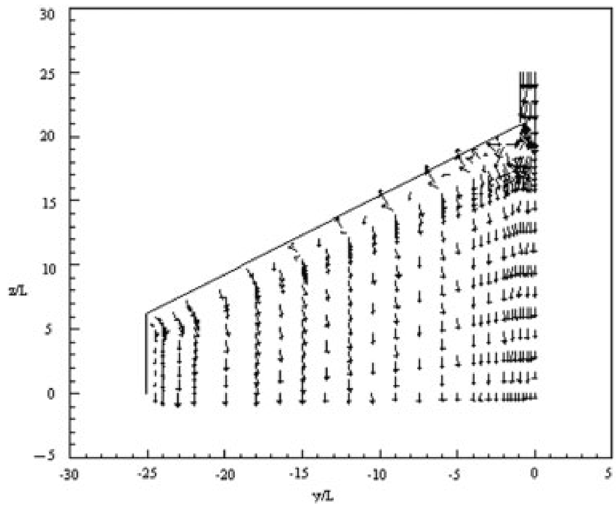

Figure 5 The flow pattern at the central plane of the distributor from the simulation.

EFFECTS OF THE GEOMETRIC PARAMETERS ON THE FLOW UNIFORMITY

Numerical simulation cannot give an explicit design equation for coat hanger distributor as the analytical one-dimensional method does. Therefore, the design of coat hanger distributor based on the FEM simulation is actually a computer-aided "trial-and-error" procedure. To begin the design, a primitive design must be determined first. The polymer fluid flow in the primitive distributor is then computed using the FEM. If the flow distribution at the distributor outlet is not uniform as required, the distributor's geometric parameters such as manifold angle and land height will be changed until an optimum distributor is found out. In this paper, the uniformity of the flow distribution at the distributor outlet is evaluated by a statistical measure, the coefficient of variation (CV). The coefficient of variation is defined as the standard deviation over the mean of a set of data. Lower CV indicates less variation and better uniformity of flow distribution across the distributor width.

A coat hanger distributor with linearly taper manifolds is determined as the primitive design. The manifold radius R is given by the following relation, which is derived using one-dimensional lubrication model[11–12]:

$$R = R_0\left(1 - \frac{y}{W}\right)^{n/(3n+1)} \tag{7}$$

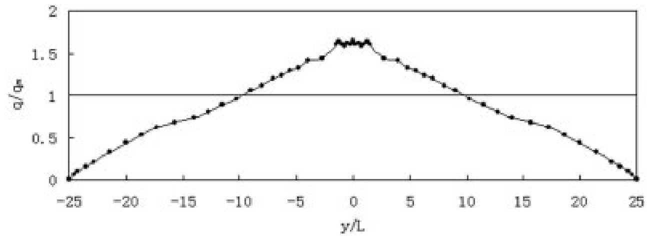

Figure 6 The transverse flow distribution at distributor outlet (manifold angle 15°).

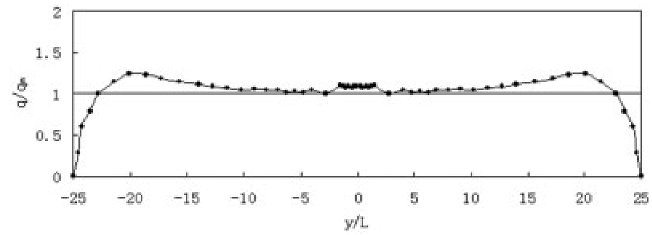

Figure 8 The transverse flow distribution at distributor outlet (manifold angle 35°).

R_0 is the radius of the manifold inlet, W is the half width of coat hanger distributor, and n represents the power law index. In the simulation, the power-law index is set to be 0.35 and all dimensions are normalized with the inlet tube radius L. Thus, the geometry of the primitive distributor is determined. The radius of manifold inlet R_0 is 1.2, the half width of distributor W is 25, the land height B is 2.5, the slit opening D is 0.05, and the manifold angle α is 15°. The velocity at the inlet is 1, as all velocities are normalized with the velocity V at the inlet in the simulation.

Once the velocity distribution is determined through the three-dimensional finite element simulation, the flow rate q per unit distributor width at distributor outlet can be calculated by using the following formula:

$$q(y) = \int_{-D/2}^{D/2} v_3 dx \tag{8}$$

where v_3 is the velocity component along z direction at the distributor outlet, and D is the slit opening. Once the value q along the slit outlet is obtained, their mean q_m can be computed.

Figure 6 shows the transverse flow distribution at the outlet of the primitive distributor design, where the flow rate q is normalized with the mean q_m. It can be seen that the flow rate reaches the maximum at the center of the distributor outlet and then decreases almost linearly after a small range of fluctuation. The CV value of the flow distribution is 0.513. Such a design is undesirable in the practical use, so it should be made further improvement for the uniform flow distribution.

Effect of manifold angle on the flow distribution

The manifold angle of the primitive coat hanger distributor is increased to find a better design. The coat hanger distributors with manifold angle of 30°, 35°, and 40° are investigated. Their transverse flow distributions at distributor outlet are shown in Figures 7–9 respectively.

With regard to the 30° coat hanger distributor, the maximum flow rate and the small range of fluctuation remain at the center of the distributor outlet. However, it happens at a lower level compared to the case of the l5° coat hanger distributor. Then, the f1ow distribution tends to be flat and agrees with the average distribution well. As expected, the flow rate begins to decrease dramatically when the melt is approaching the distributor walls due to the application of nonslip boundary condition in the simulation. By comparing Figures 7, 8, and 9, it can be seen that the flow distribution at distributor outlet tends to be more concave in the middle part of the distributor and more convex at the both ends of the distributor as the manifold angle increases. This phenomenon is supposed due to the change of the path of the fluid passing from the inlet to the outlet. At a lower manifold angle, the flow path of the fluid in the middle part is shorter than that near the both ends, so the flow rate is higher in the middle part than near the both ends. However, as the manifold angle increases, the flow path of the fluid in the middle part will have a more increase than that

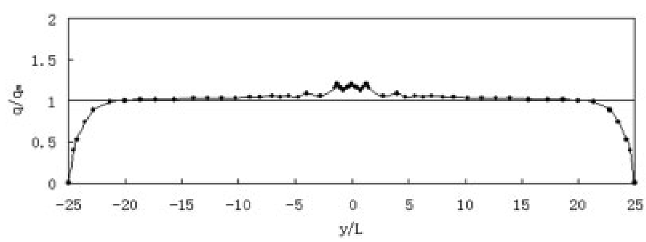

Figure 7 The transverse flow distribution at distributor outlet (manifold angle 30°).

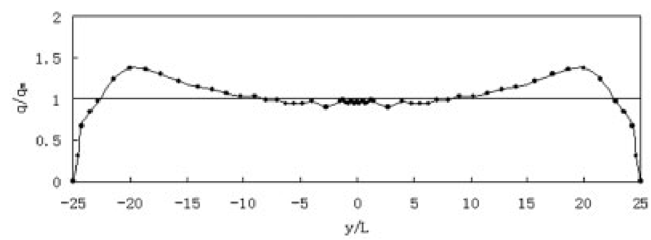

Figure 9 The transverse flow distribution at distributor outlet (manifold angle 40°).

near the both ends. When the manifold angle is increased to a specific angle, all the flow paths tend to be equal and hence the flow distribution at the outlet becomes uniform. When the manifold angle is continually increased, the balance will be destroyed and the flow rate near the both ends tends to be higher than that in the middle part.

As can be seen, the 30° coat hanger distributor has the best uniformity to distribute the melt across the width among the above four distributors. This observation is confirmed by comparing their CV values. The CV values are 0.119, 0.125, and 0.15, respectively, for the 30°, 35°, and 40° coat hanger distributor. However, the flow rate at the center of the distributor outlet still fluctuates at a fairly high level. It may be because that the irregular flow happened at the joint of the manifolds and the inlet tube extends its influence to the distributor outlet. It is supposed that this influence is possible to be weakened by extending the land height.

Effect of land height on the flow distribution

The effect of the land height on the flow distribution is investigated by increasing the land height of the 30° coat hanger distributor. As shown in Figures 10 and 11, the flow rate distribution at the outlet is becoming more uniform with the increase of land height. The CV value decreases from 0.119 to 0.115 when the land height increases from 2.5 to 3.5, while the CV value decreases continually to 0.107 when the land height increases to 5. The improvement of the uniformity of the flow distribution is supposed to be because the polymer fluid flow in the slit becomes more developed with the increase of the land height. Although the uniformity of flow distribution at the distributor outlet, especially in the middle part of it, will improve with the increase of land height, it should be taken into account in practice that extending land height will lead to the increase of the whole distributor height and hence the increase of energy consumption.

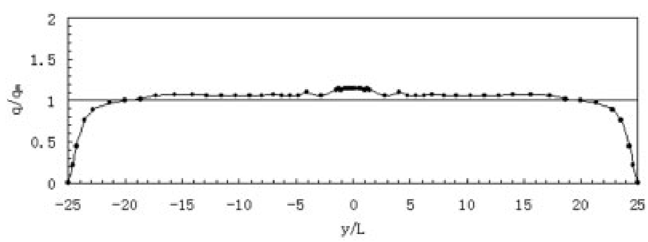

Figure 10 The transverse flow distribution at distributor outlet (manifold angle 30°, land height 3.5).

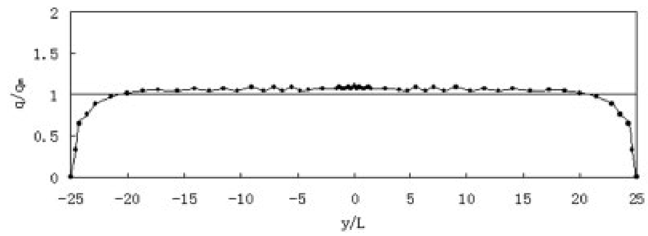

Figure 11 The transverse flow distribution at distributor outlet (manifold angle 30°, land height 5).

CONCLUSIONS

The nature of the complicated flow of non-Newtonian fluid in the complex geometry determines that it is a difficult task to design an optimum coat hanger distributor used for meltblown process. A "trial-and-error" design procedure based on the three-dimensional finite element simulation of polymeric fluid flow in the distributor is proved effective. The flow distribution at the distributor outlet is influenced by the distributor's geometric parameters such as manifold angle and land height. As the manifold angle increases, the flow distribution curve appears to transform gradually from a "hill" shape to a "bone" shape. The phenomenon implies that there exists an optimum manifold angle for the coat hanger distributor to distribute the melt uniformly. Whether the manifold angle is increased or decreased from the optimum angle, the uniformity of the flow distribution will deteriorate. In addition, the uniformity of flow distribution at distributor outlet, especially the fluctuation at the central part, will be improved by increasing the land height.

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