Numerical Analysis of the Stagnation Phenomenon in the Coat-Hanger Die of Melt Blowing Process

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ABSTRACT: In this paper the stagnation phenomenon occurred in the coat-hanger die is investigated using a three-dimensional finite element method to simulate the polymer fluid flow in the die. The stagnation zone is defined to evaluate the degree of the stagnation. The effects of the inlet flow rate, the slot gap, the manifold angle, and the power-law index on the stagnation are then analyzed numerically. It is found that the manifold angle and the geometric abrupt change between the manifold and the slot have significant influence on the stagnation, and a coat-hanger die with tear-dropped manifolds to be capable of diminishing the stagnation. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 108: 2523–2527, 2008

Key words: simulations; stagnation; coat-hanger die; melt blowing

INTRODUCTION

Coat-hanger dies are extensively used for the production of polymer sheet, film, and melt blown nonwoven. Searching for the optimal flow channel geometry of a coat-hanger die has been a major research interest for many years. Generally, two approaches have been adopted to study the design and the performance of a coat-hanger die. The first is the analytical method based on the one-dimensional lubrication approximation theory.[1] It can give the design equations of the manifolds. 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. To know the nature of the polymer flow in it and thereby provide a more effective design method, numerical methods are used to simulate the polymeric fluid flow in the coat-hanger die.[2] The velocity and pressure fields in the coat-hanger die can be completely determined without serious assumptions by using the three-dimensional numerical simulations.

To date, most research work are focused on searching for an optimal coat-hanger die with an ability to distribute the polymer fluid uniformly, while neglecting the pernicious effects of the stagnation phenomenon occurred in circular manifolds. Material entering the stagnation area will have a longer residence time compared with the bulk of the polymer melt. It will cause some production problems such as hold-up or degradation and the deterioration of the product quality. The situation is more serious in a melt blowing die than in a film or sheeting die, as the melt blowing die usually has no mechanical adjustments to compensate for variations in polymer flow. Huang et al. reported the stagnation phenomenon occurred in the coat-hanger die.[3] However, they just gave a simple qualitative analysis. In this article, we investigate the stagnation phenomenon occurred in the coat-hanger die quantitatively using the three-dimensional finite element method.

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NUMERICAL SIMULATIONS

In Figure 1 is shown the schematic diagram of a melt blowing coat-hanger die and the coordinate system. Assuming the polymer fluid flow in the melt blowing coat-hanger die is an isothermal steady flow of incompressible power-law fluid, the governing equations are written as follows:

$$\nabla \cdot v = 0 \tag{1}$$

$$-\nabla p + \nabla \cdot \tau = 0 \tag{2}$$

$$\tau = \eta \dot{\gamma} \tag{3}$$

$$\eta = K \dot{\gamma}^{n-1} \tag{4}$$

where ∇ is nabla operator, v is velocity vector, p is pressure, τ is stress tensor, $\dot{\gamma}$ is strain-rate tensor, η

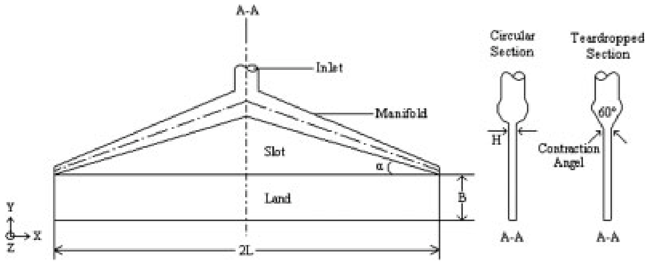

Figure 1 Schematic diagram of a melt blowing coat-hanger die.

is viscosity, K is consistence index, and n is power-law index.

Equation (1) is the mass conservation equation with incompressible constraint. Equation (2) is the momentum balance equation, where the gravity and inertia terms are neglected because the inertia force and the gravity force are much lower than the viscous force for the polymer melt flow in the coat-hanger die (Reynolds number $Re < 10^{-3}$, the ratio of Reynolds number and Froude number $Re/Fr < 10^{-2}$). Equation (3) is the constitutive equation, in which the viscosity function is described with the 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.[4]

In Table I are listed the geometric parameters of the coat-hanger die used for the simulation, i.e., the manifold inlet radius R_0, the half die width L, the die inlet radius R_{in}, the slot gap H, the land height B, and the manifold angle α. The manifold radius R is given by the following relation, which is derived using one-dimensional lubrication model:

$$R = R_0\left(1 - \frac{x}{L}\right)^{n/(3n+1)} \qquad (5)$$

Because of the symmetry, only one half of the coat-hanger die is simulated. In Figure 2 are shown the finite element meshes with 41,376 elements and 18,917 nodes. We use 8-node hexahedron elements in the slot area and 4-node tetrahedron elements in the inlet and manifold area. At the border area of the manifold and the slot, the denser meshes are used because of the abrupt change in the geometry.

In the simulation the nonslip boundary condition is applied on the die wall for the three velocity components. At the symmetry plane, zero x-component velocity and zero surface traction in y and z directions are imposed. The axial velocity component is assumed uniform at the die inlet. The volumetric flow rate at the die inlet is 5×10^{-6} m^3/s and the pressure at the die outlet is atmospheric pressure.

The Galerkin finite element method is adopted to solve the three-dimensional polymer fluid flow in the coat-hanger die. The detailed procedure has been presented in our previous paper.[5]

TABLE I
Geometric Parameters of the Coat-Hanger Die

R_0 (mm)	4
L (mm)	50
R_{in} (mm)	3
H (mm)	2
B (mm)	10
α	21°

RESULTS AND DISCUSSION

Stagnation zone

The velocity vector plot and the contour plot of the velocity magnitude at the symmetry plane are shown in Figure 3. It appears from the vector plot that there is no recirculation or vortices in the die. We can see from the contour plot that there is a low velocity area in the manifold marked by a circle, where the velocity is not more than 5% of the maximum velocity of the polymer flow in the die. Melt entering this area is difficult to flow into the slot and hence has a longer residence time. This is the stagnation phenomenon we discuss.

To investigate the stagnation inside the manifold, we intercept four different sections parallel to the symmetry plane along the axial direction of the manifold. As shown in Figure 4, the stagnation decreases with the increment of the distance from the symmetry plane and gradually disappears. It shows that the stagnation is apt to occur in the

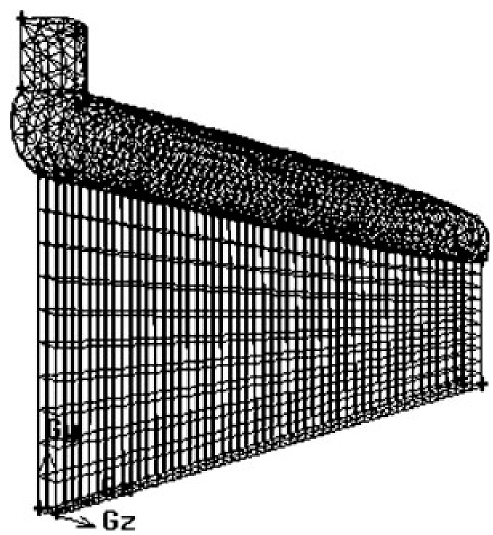

Figure 2 The finite element meshes.

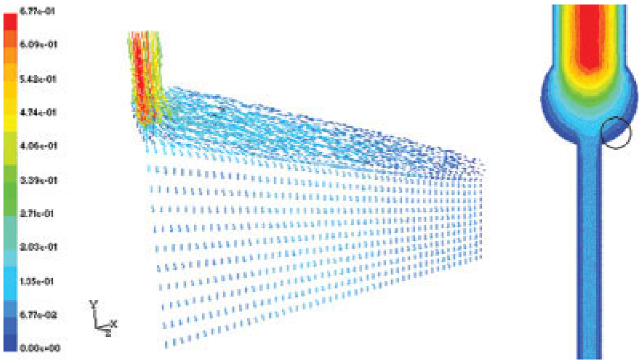

Figure 3 Velocity magnitude vector plot and magnified contour plot at the symmetry plane. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 5 Stagnation zone for different volumetric flow rates. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 6 Stagnation zone for different slot gap. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

manifold close to the inlet area and becomes the worst at the symmetry plane. Therefore, we can use the area of the stagnation zone at the symmetry plane to evaluate the degree of the stagnation occurred in coat-hanger dies. The bigger the area of the stagnation zone, the more serious the stagnation is. We define the stagnation zone at the symmetry plane as such a low velocity area that the velocity in this area is not more than 5% of the maximum velocity and the height above the border of the manifold and the slot is 2 mm as shown in Figure 4A. Selecting 2 mm as the height of the stagnation zone is because the stagnation in this region is the most serious.

Effects of the inlet flow rate, the slot gap, the manifold angle and the material on the stagnation

The areas of the stagnation zones for three different volumetric flow rates are computed for the PE melt, when the slot gap is kept fixed at 2 mm and the manifold angle is kept fixed at 21°. It appears from Figure 5 that the areas of the stagnation zones are identical although the inlet volumetric flow rates are different. It indicates that the inlet volumetric flow rate has no effect on the stagnation. This is because the low velocity area with reference to the maximum velocity inside the die keeps constant although the absolute velocity in the stagnation zone increases as the inlet flow rate increases.

The effect of the slot gap on the areas of the stagnation zones is also investigated for the PE melt. In the simulation, the inlet flow rate of 5×10^{-6} m^3/s and the manifold angle of 21° are kept fixed. It can be seen from Figure 6 that the area of the stagnation zone increases as the slot gap decreases. When the slot gap decreases from 3 to 2 mm or 1 mm, the area of the stagnation zone increases by 30% or 46%, respectively. It indicates that the large geometric abrupt change between the manifold and the slot is the main cause of the stagnation.

The areas of the stagnation zones for different manifold angles are obtained for PE melt with the fixed inlet volumetric flow rate of 5×10^{-6} m^3/s and slot gap of 2 mm. It appears from Figure 7 that the area of the stagnation zone decreases with the increase of the manifold angle, indicating the significant effect of the manifold angle on the stagnation. This phenomenon can be attributed to the reduced resistance of the manifold to the polymer fluid flow with the increase of the manifold angle.

When the inlet flow rate, the slot gap and the manifold angle are kept fixed at 5×10^{-6} m^3/s,

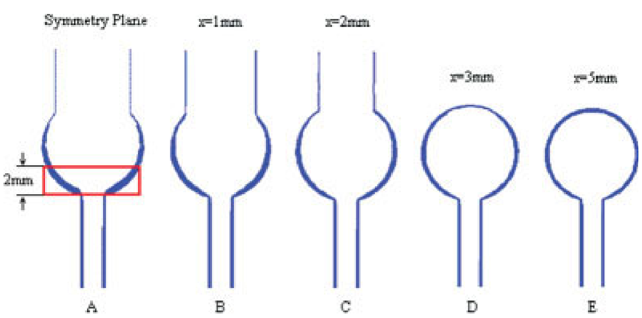

Figure 4 Magnified local plot of low velocity area at different section. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

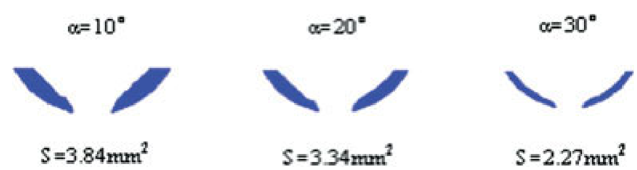

Figure 7 Stagnation zone for different manifold angle. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Figure 8 Stagnation zone for different material. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

2mm and 21° respectively, the effect of the polymer material on the area of the stagnation zone is investigated. The areas of the stagnation zones for PE, PP, and PET are shown in Figure 8. The material properties of PE, PP, and PET are listed in Table II. It appears from Figure 8 that the area of the stagnation zone varies with the materials. The stagnation area tends to increase gradually as the power law index increases.

Coat-hanger die with tear-dropped manifolds

It is known from the above analysis that the stagnation can be diminished by increasing the manifold angle and the slot gap. However, the geometric abrupt change between the manifold and the slot cannot be eliminated or designed to be very small due to the construction restriction for connecting the circular manifold and the narrow slot gap. The manifold angle can also not be designed too big because it will increase the die height and hence the energy consumption. Therefore, an alternative solution to decrease the stagnation is to change the shape of the manifold cross section.

The polymer fluid flow is simulated in a tear-dropped coat-hanger with a contraction angle of 60° as shown in Figure 1, when the other geometric parameters are kept constant, as shown in Table I. The contour plot of the velocity at the symmetry plane is shown in Figure 9. It can be seen that the area of the stagnation zone for the tear-dropped coat-hanger decreases to 1.68 mm^2 from the 2.99 mm^2 for the corresponding circular coat-hanger. Similar results are obtained for the tear-dropped coat-hanger with the contraction angle of 45° and 75°. It reveals that the stagnation can be reduced by using the coat-hanger die with tear-dropped manifolds.

TABLE II
Material Properties

	Material		
	PE	PP	PET
K (Pa s^n)	11,500	268	3711
n	0.58	0.68	0.785
ρ (kg/m^3)	923	900	1455

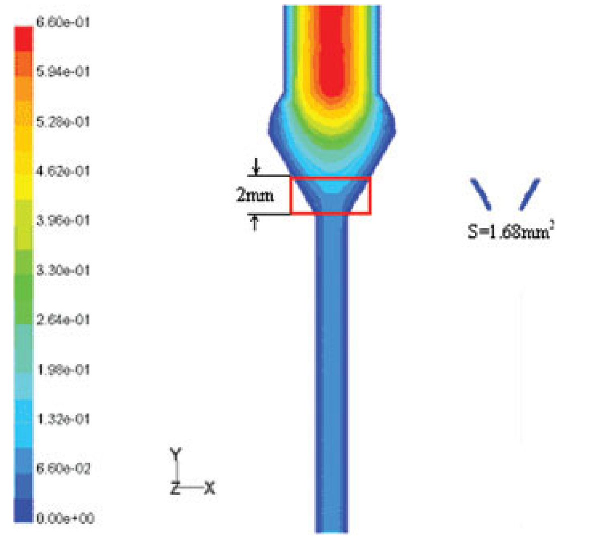

Figure 9 Contour plot of velocity magnitude at the symmetry plane for coat-hanger die with tear-dropped manifolds. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

It should be noted that the flow uniformity across the die width must be ensured whatever the shape of the manifold is. The uniformity of the flow distribution at the die outlet can be evaluated by the coefficient of variation (CV). CV is defined as the standard deviation over the mean of a set of data. Lower CV value indicates less variation and better uniformity of flow distribution across the die width. The velocity distribution at the outlet of the initial coat-hanger die with circular manifolds is plotted in Figure 10B, where v is the velocity magnitude and v_a is the average velocity. It is shown that the initial coat-hanger die can distribute the polymer fluid uniformly with 2.6% of CV value. As can be seen from Figure 10C, the uniformity of the flow distribution deteriorates and the CV value increases to 6% when the circular manifold is modified to the tear-dropped

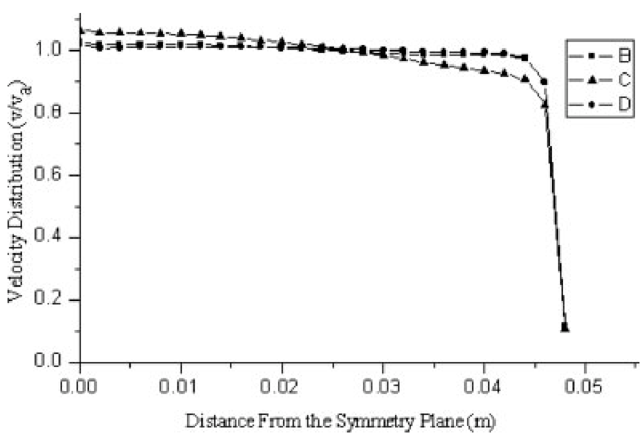

Figure 10 Velocity distributions at the die outlet.

manifold with a contraction angle of 60°. To ensure the flow uniformity, the tear-dropped coat-hanger die is optimized by changing the manifold angle through a trial and error method. It appears in Figure 10D that the flow distribution at die outlet becomes uniform when the manifold angle is 24°. The CV value is 2.3% and the area of the stagnation zone is 1.44 mm^2 for the optimized die. It reveals that demands for the flow uniformity and the stagnation can be met simultaneously by optimal design of the coat-hanger die.

CONCLUSIONS

The polymer fluid flow in a melt blowing coat-hanger die with circular manifolds is simulated using the three-dimensional finite element method. The simulation results show that the stagnation is present inside the coat-hanger die with circular manifolds and the stagnation is apt to occur at the manifold close to the inlet area. The degree of the stagnation can be evaluated by computing the area of the stagnation zone at the symmetry plane of the die. The geometric abrupt change between the manifold and the slot is one of the main causes of the stagnation and the manifold angle also has a significant effect on the stagnation. The effects of the inlet volumetric flow rate and the material properties on the stagnation are relatively insignificant.

To reduce the stagnation, one of the effective measures is to change the shape of the manifold cross section. It is found that a coat-hanger die with tear-dropped manifolds is able to not only decrease the stagnation but also ensure a uniform flow distribution at the die outlet.

References

1. Liu, T. J.; Liu, L. D. Polym Eng Sci 1994, 34, 541.
2. Sun, Q.; Zhang, D. J Appl Polym Sci 1998, 67, 193.
3. Huang, Y. H.; Richard, G. C.; Barry, H. J. Adv Polym Technol 2004, 23, 111.
4. Pittman, J. F. T.; Sander, R. Int Poly Process 1994, 9, 326.
5. Wang, X. H.; Chen, T.; Huang, X. B. J Appl Polym Sci 2006, 101, 1570.