Optimal Geometry Design of the Coat-Hanger Die with Uniform Outlet Velocity and Minimal Residence Time

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ABSTRACT: In this article a method combining the orthogonal array design and the numerical simulation is used to optimize the geometry parameters of the coat-hanger die with uniform outlet velocity and minimal residence time. The outlet velocity and the residence time are obtained by simulating the three-dimensional nonisothermal polymer flow in the coat-hanger die, while the optimal geometry design is accomplished via the orthogonal array method. The effects of the manifold angle, the land height and the slot gap on the outlet velocity and the residence time are investigated. The results show that the effects of all the three parameters are significant for the outlet velocity. For the residence time, the manifold angle and the slot gap are the significant factors, while the effect of the land height is insignificant. The optimal geometry parameters of the coat-hanger die achieved in this study are that the manifold angle is 5°, the height land is 70 mm, and the slot gap is 3 mm. J Appl Polym Sci 123: 2511–2516, 2012

Key words: coat-hanger die; orthogonal array method; simulation; residence time

INTRODUCTION

The coat-hanger dies are widely used in the polymer processing for the sheets, films, and nonwoven. Both the geometrical and material quality of the products are governed by the uniformity of flow rate and residence time distributions of the polymer flowing in the die. To satisfy these conditions, its design is mainly done empirically. Through a trial-and-error process, designers may predict the most adequate die geometry. However, this iterative process is time-consuming and will cause material waste. Therefore, computer simulation becomes a good approach to eliminating the need for costly modification of a poorly designed coat-hanger die.

The design problem of the coat-hanger dies was investigated by many investigators. Some of these analysis[1–3] can be termed as the one-dimensional models of the flow in the manifold and the slot, which neglects the interaction between the two flows in the manifold and the slot. Some of the numerical analyses[4–6] were carried out based on the two-dimensional flow model and the approximation. The two-dimensional analysis need relatively lower load of computation and can be applied easily. But the application of the two-dimensional analysis cannot take full account of the geometrical features of the die inlet and the manifold. Na et al.[7] studied the coat-hanger die design parameters with the three-dimensional model of isothermal flow of power-law fluid. Liu et al.[8] combined both the simple 1D lubrication approximation and the 3D finite element simulation to design an extrusion die with Bingham viscoelasticity fluid model. Wang et al.[9,10] simulated the 3D flow of the polymer in the coat-hanger die and verified the simulation results with laser Doppler velocimetry (LDV) and particle image velocimetry (PIV) experiments. In addition, Chen et al.[11] employed the orthogonal array method to investigate the influences of some factors involved in the design of a coat-hanger manifold in term of formulae obtained using analytic methods. Unfortunately, they did not consider the effect of the residence time of the polymer in the coat-hanger die. The residence time is the time taken by a polymer melt in passing along a specified flow stream through the die.[12] Residence time was judged to be one of important design constraints to flow uniformity, due to a long residence time through the die far end which often causes inferior qualities of the far end part to the center part in the sheet or film extrude because of thermal degradation of polymer melt in the die. In this work, we focus on a uniform velocity distribution and minimal residence time. Then, the numerical simulation and the orthogonal

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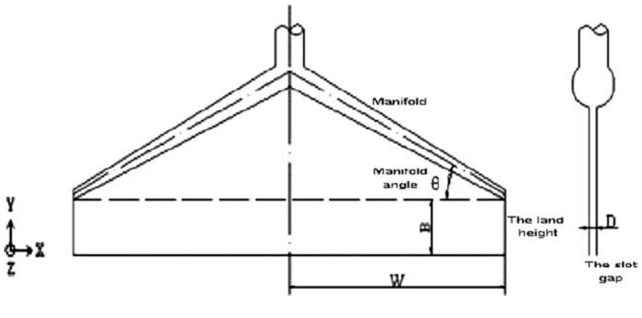

Figure 1 Schematic diagram of a coat-hanger die.

array design have been adopted to optimize the geometry parameters of the coat-hanger die.

Numerical simulations

Figure 1 shows the coat-hanger die with linearly tapered manifolds used in the simulation.

Assuming the polymer fluid flow in the coat-hanger die is an incompressible nonisothermal steady flow of Carreau fluid, the governing equations[13] are written as follows:

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

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

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

$$\eta = \eta_0 \left[1 + \left(\lambda \dot{\gamma}\right)^2\right]^{\frac{n-1}{2}} \tag{4}$$

Where $\bigtriangledown$ is nabla operator, v is velocity vector, p is pressure, τ is stress, $\dot{\gamma}$ is strain-rate tensor, η is viscosity, η_0 is the viscosity at zero shear rate, and λ is a time constant obtained from the viscosity curve of the material. η is not only related to the power-law index but also is influenced by the temperature T. This article adopts the approximate Arrhenius law model for it.

$$H(T) = \exp[-\alpha(T - T_\alpha)] \tag{5}$$

where α is the viscosity-temperature coefficient, T_α is the reference temperature.

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 $\mathrm{Re}<10^{-3}$, the ratio of Reynolds number and Froude number $\mathrm{Re/Fr} < \mathrm{Fr} < 10^{-2}$). Equation (3) is the constitutive equation, in which the viscosity function is described with the Carreau model eq. (4).

Table I lists the geometric parameters of the coat-hanger die and the material parameters used in the Carreau model.

In the numerical simulation, because of the symmetry, only one-forth part of the coat-hanger die is simulated so that calculation time was much saved. 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[14–16] 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. At the die inlet, only the axial velocity component exists and is assumed to have full-developed velocity profile. The volumetric flow rate at the die inlet is $1.5 \times 10^{-5} \mathrm{m}^3/\mathrm{s}$ 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 applicability of the numerical scheme was experimentally verified quantitatively and qualitatively using laser Doppler velocimetry (LDV) and particle image velocimetry (PIV), respectively. The detailed procedure of the simulation and the experimental verification has been presented in our previous article.[9]

Figure 2 shows the contours of velocity magnitude in the initial coat-hanger die with the manifold angle 15°, the land height 70 mm and the slot gap 3 mm. It can be seen that the flow rate reaches the minimum at the center of the distributor outlet and then increases almost linearly after a small range of fluctuation. The velocity increases gradually from the center to the edge of coat-hanger die. Figure 3 shows the streamlines which are assumed to start at the same time from the entrance to the outlet of the die, and presents the different residence times in different regions of the die.

Figure 4 presents the distribution of outlet velocity and residence time in the initial coat-hanger die. It shows that the coefficient of variation (CV) of outlet velocity reaches to 34% and the average residence

TABLE I
Variable Values and Material Parameters Used in the Simulation

Variable	Value
Radius of the entrance R_i	45 mm
Half die width W	600 mm
Melt density ρ at 230 °C	900 $\mathrm{kg/m^3}$
Total volumetric flow rate $4\dot{Q}_0$	$1.5 \times 10^{-5}\ m^3/s$
Zero-shear viscosity η_0	26,470 Pa s
Time constant λ	2.15
Power-law index n for PP	0.38
Viscosity-temperature Coefficient α	0.02°C
The reference temperature T_α	230°C
Heat capacity per unit volume C_p	2,100 J/kg °C

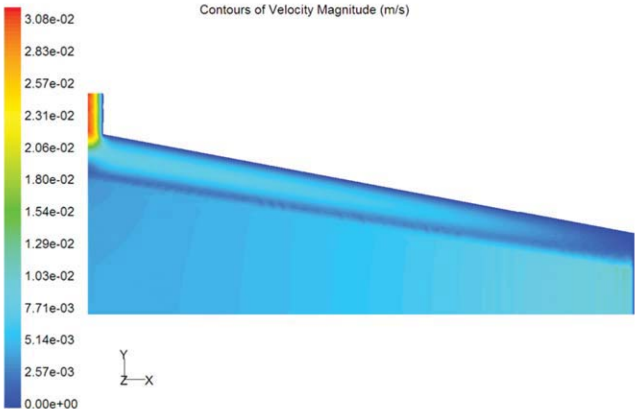

Figure 2 Coutours of velocity magnitude in the coat-hanger die. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

time reaches to 547 s. The larger CV value and the longer residence time can cause thermal degradation in coat-hanger die which in turn leads to the inferiority of the quality and the decomposition of polymer. Therefore, the coat-hanger die should be optimized further.

Orthogonal array design method

It is difficult to investigate the influence of each determinant because many factors are involved in the coat-hanger die design.[17] To optimize the coat-hanger die, we apply the orthogonal array design method in this research. The method is a powerful experimental technique which can increase the productivity and quality of a product with a minimum amount of trials.[18] This technique performs a partial factorial analysis set by the orthogonal array chosen. Matsubara[1,3] analyzed the average velocity of outlet and residence time distribution of polymer melt across the die width in a common linearly tapered coat-hanger die and gave the analytical formula that showed the manifold angle, the land height and the slot gap are the most important parameters affecting the performance of the coat-hanger die. Table II gives three different levels for the three factors. Then a three-factor and three-level orthogonal array $L_{27}(3^3)$ shown in Table III was established for our research. The other geometric parameters and material parameters are described in Table I. The goal of the following work is to determine the coat-hanger die geometry that based on the smaller CV value of outlet velocity and residence time.

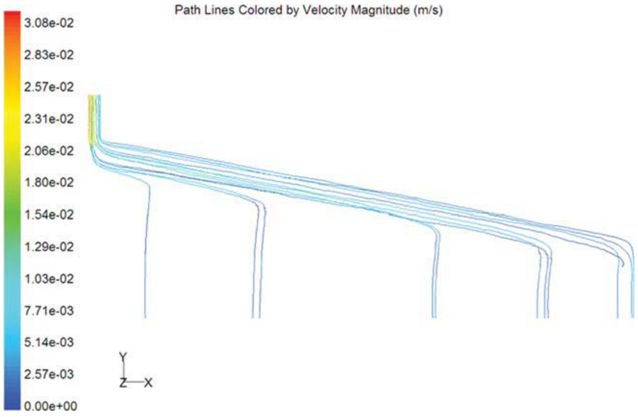

Figure 3 Streamlines in the coat-hanger die. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

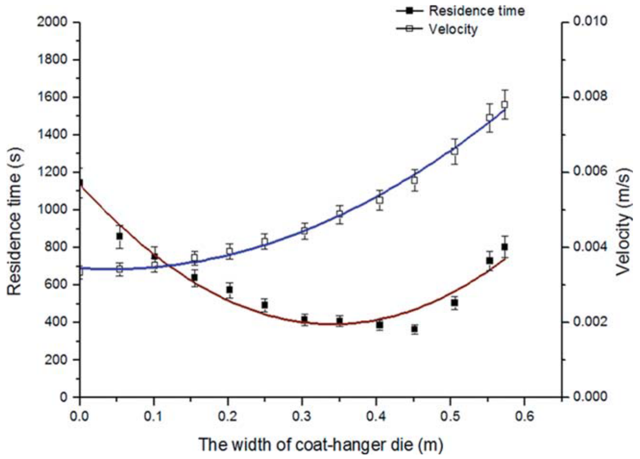

Figure 4 The distribution of outlet velocity and residence time of the initial coat-hanger die. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

RESULTS AND DISCUSSION

Table III illustrates the plan of orthogonal array design and the simulation experimental results. For each trial, we use simulation to calculate the CV of outlet velocity and the average residence time. In Table III, K_i is the sum value of the CV of outlet velocity and T_i is the sum value of average residence time for the factors at i level ($i = 1, 2, 3$). R is the difference between the extreme values of the data. The label R_k and R_t stand for the CV of outlet velocity and the average residence time respectively.

Figure 5 shows that the mean values of the CV of outlet velocity against the levels of the three factors. It is obvious that the effects of the manifold angle, the land height and the slot gap are dramatic. The

TABLE II
Levels of the Factors Used in the Design

Factors	Level 1	Level 2	Level 3
Manifold angle/° (A)	15	10	5
The land height/mm (B)	50	70	90
The slot gap/mm (C)	2	3	4

TABLE III
The Plan of the Orthogonal Array Design and the Results

Trial no. No.	A	B	C	CV of outlet velocity (%)	Average residence time (s)	Standard deviation of residence time
1	1	1	1	34.48	278	61
2	1	1	2	36.95	343	67
3	1	1	3	26.91	503	122
4	1	2	1	35.02	321	83
5	1	2	2	31.29	547	181
6	1	2	3	20.73	286	141
7	1	3	1	23.78	317	83
8	1	3	2	21.03	592	176
9	1	3	3	17.76	480	120
10	2	1	1	27.40	244	47
11	2	1	2	22.70	285	45
12	2	1	3	18.13	327	36
13	2	2	1	21.63	283	78
14	2	2	2	18.32	377	103
15	2	2	3	12.77	534	125
16	2	3	1	17.96	361	93
17	2	3	2	15.33	356	73
18	2	3	3	11.89	421	82
19	3	1	1	15.27	207	84
20	3	1	2	12.21	233	70
21	3	1	3	8.50	301	146
22	3	2	1	11.82	244	105
23	3	2	2	7.70	292	71
24	3	2	3	5.20	376	77
25	3	3	1	9.41	264	88
26	3	3	2	6.69	323	84
27	3	3	3	4.03	362	65
K1	247.95	202.55	196.77			
K2	166.13	164.48	172.22			
K3	80.83	127.88	125.92			
R_k	167.12	74.67	70.85			
T1	3667	2721	2519			
T2	3188	3260	3348			
T3	2602	3476	3590			
R_t	1065	755	1071			

The goal programming function for optimal coat-hanger die $f(x) = M\left[\frac{f_V(x)-f_{V\min}(x)}{f_{V\max}(x)-f_{V\min}(x)}\right] + N\left[\frac{f_T(x)-f_{T\min}(x)}{f_{T\max}(x)-f_{T\min}(x)}\right]$

CV of outlet velocity decreases linearly with the increase of the manifold angle, the land height and the slot gap. From the value of R_k in Table III, it can be seen that the effect of manifold angle is the most significant on the CV of outlet velocity.

Figure 6 indicates that the residence time decreases with the increase of the manifold angle but increases as the land height and the slot gap increase. From the value of R_t in Table III, it is seen that the manifold angle is also the most significant factor and the land height is the insignificant factor for residence time.

Besides the above visual analysis, the results of simulation experiments are also discussed with analysis of variance. Tables IV and V show the significance of the three factors. They illustrate that Factors A (manifold angle) and C (the slot gap) have a significant effect on both the velocity of outlet and residence time, while Factor B (the land height) is significant only for the velocity of outlet. The results are consistent with the visual analysis.

As shown in Table III, trial No.27 (A3B3C3) is the optimal coat-hanger die for the uniform velocity when A (manifold angle) is 5°, B (the land height) is

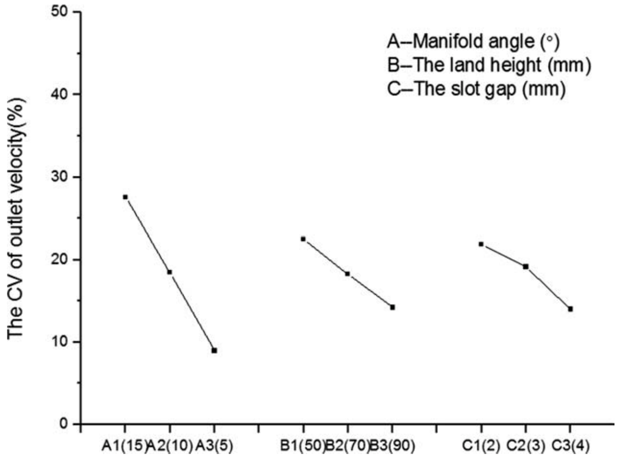

Figure 5 The CV of outlet velocity against the level of three factors.

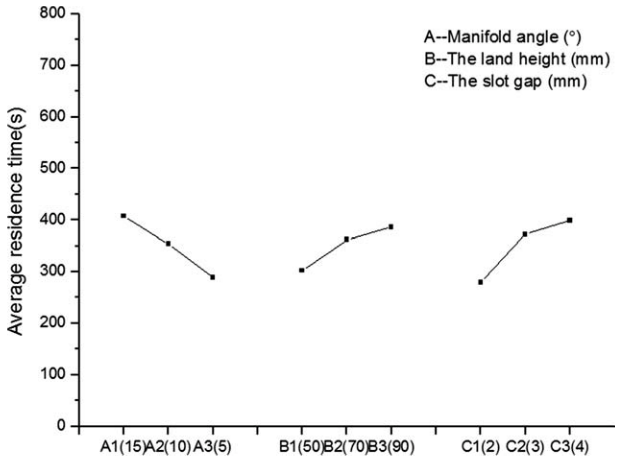

Figure 6 The residence time against the level of three factors

90 mm and C (the slot gap) is 4 mm. The CV of outlet velocity of this coat-hanger die is 4.03%. Considering the residence time, A3B1C1 is the optimal coat hanger die geometry parameters, when the residence time is 207 s. To meet the demands for the uniform outlet velocity and minimal residence time simultaneously, we use goal programming function, eq. (6), to calculate the optimal of coat-die.

$$f(x) = M\left[\frac{f_V(x) - f_{V\min}(x)}{f_{V\max}(x) - f_{V\min}(x)}\right] + N\left[\frac{f_T(x) - f_{T\min}(x)}{f_{T\max}(x) - f_{T\min}(x)}\right] \quad (6)$$

where $f_V(x)$, $f_T(x)$ are the CV of velocity and residence time value respectively, for every coat-die, $f_{V\min}(x)$, $f_{T\min}(x)$ are the minimum CV of velocity and residence time value respectively. $f_{V\max}(x)$, $f_{T\max}(x)$ are the maximum CV of velocity and residence time value respectively, $M = 0.6$, $N = 0.4$ (M, N based on expert evaluation method). The design of trial No.23 (A3B2C2) can give the optimal coat-hanger die with the CV of outlet velocity 7.7% and residence time 292 s, when the manifold angle is 5°, the height land is 70 mm, and the slot gap is 3 mm. Figure 7 shows the contour of the outlet velocity and residence time of trial No.23 coat-hanger die.

TABLE IV
Analysis of the CV of Velocity Variance

	Sum of squares	*df*	Mean square	*F*	Significance
A	1552	2	776	51.15	**
B	310	2	155	4.26	**
C	288	2	244	6.72	**
Δ*e*	303.4	20	15.17		

** Indicates significant at level α = 0.05.

TABLE V
Analysis of the Residence Time Variance

	Sum of squares	*df*	Mean square	*F*	Significance
A	63224	2	31,612	4.78	**
B	33600	2	16,800	2.53	
C	70105	2	35,052.5	5.27	**
Δ*e*	132805	20	6,640.25		

The velocity at the outlet, which is better than most of the twenty-seven die above meanwhile residence time in the same coat-hanger die is also shorter than most of them. From the optimal coat-hanger die, the uniform of outlet velocity and short residence time can be gained. It will avoid the degradation of polymer.

CONCLUSIONS

In this study, the three level $L_{27}(3^3)$ orthogonal array design method and computational fluid dynamics (CFD) technique were integrated to research the effects of the manifold angle, the land height and the slot gap of the coat-hanger die on the distribution of outlet velocity and residence time. The simulation results reveal that the CV of outlet velocity decreases with the increase of the three factors. Meanwhile, the residence time increase as the land height and the slot gap increase. The manifold angle and the slot gap are significant factors for the velocity of outlet and residence time, while the height land is minor significant for the residence time. The optimal geometry parameters of the coat-hanger die achieved in this study are: the manifold angle is 5°, the height land is 70 mm, and the slot gap is 3 mm.

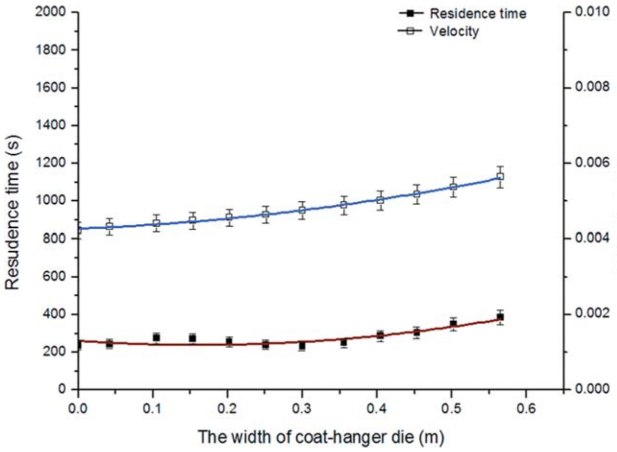

Figure 7 The distribution of outlet velocity and residence time of the optimal coat-hanger die. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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