

컴퓨터를 이용한 Internal 혼합기의 설계

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(1990년 8월 24일 접수)

Computer Aided Design for Internal Mixer

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(Received August 24, 1990)

요 약

최근 고분자 산업의 발달과 함께 고분자 혼합공정에 대한 연구와 더불어 internal 혼합기에 대한 관심이 고조되어 왔다. 본문에서는 효율적인 로우터 고안을 위하여 수학적 모델을 이용하는 computer aided design을 다루었다.

Computer aided design하기 위하여 고려된 인자는 유변학적 성질, 작업조건, 로우터의 형상이었으며 고안된 혼합기의 평가는 로우터 날에서의 응력과 순환시간을 사용하였다.

Abstract — Recently the internal mixer has been considered as an important machine in polymer processing with development of the mixing technology. This paper studied a rational engineering rotor design through computer aided design (CAD) using mathematical model. For these rheological properties of the polymer material, operational conditions and rotor dimensions were considered as design variables. The stress field at the flight tip and the circulation time were used to evaluate the designed rotor.

Key words: Internal mixer, Computer aided design, Circulation time Dispersive mixing, Distributive mixing.

Introduction

Internal mixers are usually used in the first step of the polymer processing. The step involves blending, compounding and mixing. Generally, the stock goes to a mill or extruder after compounding in an internal mixer. For example, Fig. 1 shows the tire manufacturing process. Therefore, internal mixers have an important role in controlling the quality of the final products. The various

machinery manufacturing companies have developed machines having the ability to handle fluids of the appropriate rheological properties and having suitable mixing.

The development of counterrotational twin rotor internal mixer seems to be associated with the 1877 German patent of Freyburger [1], which led to the founding of firm Warner and Pfleiderer [2]. Later Warner and Pfleiderer developed various rotors. The most important internal mixer patent

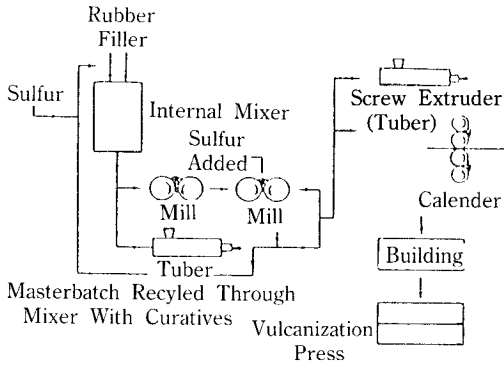


Fig. 1. Fabrication processes for conversion of rubber into tires

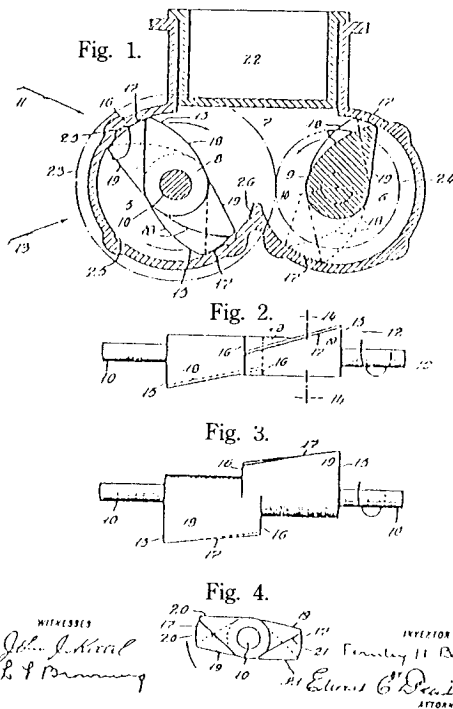


Fig. 2. Patent of banbury mixer (U. S. Patent 1,200, 070)

is that of Banbury in 1916 [3] (Fig. 2).

The Banbury machine was manufactured by the Birmingham Iron Foundry (later Farrel Corporation). Mr. Banbury developed continuously [4-7] in the Farrel Corporation. Krauss Maffei Co. [8] invented two flights rotor which was shaped elliptical. Kobe Steel Co. [9] joined the development four wing rotor recently (Fig. 3).

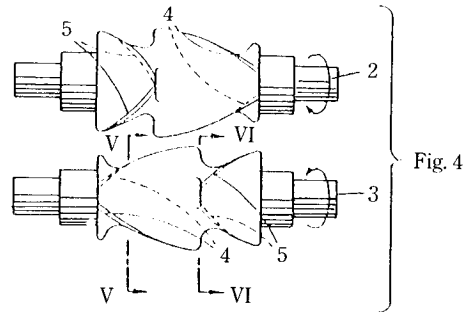


Fig. 3. Patent of 4 wing type internal mixer (U. S. Patent 4,234,358)

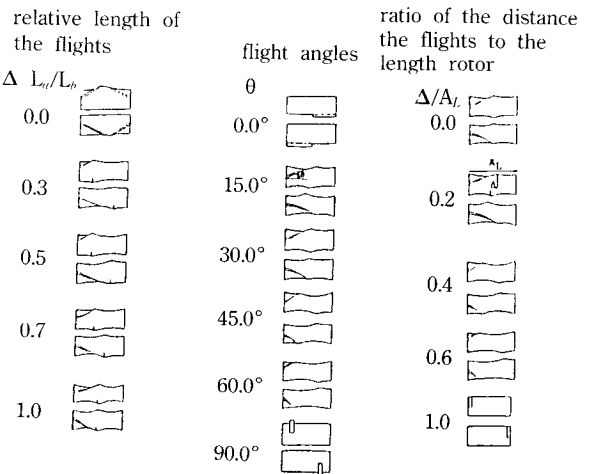


Fig. 4. Rotor designs analyzed in this paper

Design Variables

Geometrical variables

The flight geometry in the design of the rotors was considered because it has a profound effect on the mixing of polymer. Here flight angle, flight

Table 1. The Geometry Functions of the rotors

Inventor	Year	θ	L_2/L_1	Flight Number
Pointon[10]	1915	$55^\circ \pm 5^\circ$	0	1
Banbury[3]	1916	$15^\circ \pm 5^\circ$	1	2
Ford[11]	1951	$25^\circ \pm 10^\circ$	0.3	2
Grubenmann[12]	1961	30°	1	2
Tyson[13]	1966	$30^\circ \pm 5^\circ$	0.5	4
Matsuoka[14]	1968	$25^\circ \pm 5^\circ$	17/26	4
Koch[15]	1969	$45^\circ \pm 5^\circ$	1	2
Critxell[16]	1972	30°	2/3	2
Wiedmamm[17]	1980	$35^\circ \pm 5^\circ$	2/5	4
Sato[9]	1981	$20^\circ \pm 5^\circ$	0.1-0.48	4

length and distance between flights were considered as design variables. Fig. 4 shows the designs of the rotor with various design variables. Table 1 summarizes the various flight geometries that have been described in the patent literature [10-17]. The following parameters were also considered: rotor diameter, length of the rotor and clearance between rotor and chamber.

Rheological variables

Viscosity as a rheological variable was considered in this study. Polymer shows highly non-Newtonian Behavior. The viscosity determines power index n , and other experimental constants. The viscosity function is very important in determining the flow behavior in an internal mixer. Following rheological model was used

$$\eta = \frac{\eta_0}{1 + A \left(\frac{U}{H} \right)^{1-n}} \quad (1)$$

Where η ; shear viscosity
 η_0 ; zero shear viscosity
 A ; experimental constant
 H ; clearance between rotor and chamber
 U ; rotor speed
 n ; power index

Operational variables

Rotor speed was considered as operational condition. The stress history (associated with dispersive mixing) at the flight tip and circulation time (asso-

ciated with distributive mixing) were reflected through our choice of operational variable.

Generally faster rotor speed makes shear stress increases and circulation time decreases.

Program Contents

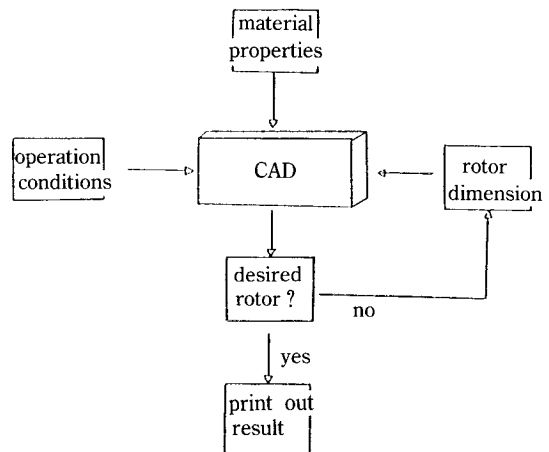
Significant number of trials and adjustment are necessary before satisfactory results are obtained. It becomes necessary from both economic and technological points of view to make more and more use of theoretical methods. Therefore, this paper includes a computer software system for rotor design through simulating flow behavior and mixing mechanisms, as shown in Fig. 5.

The aim is to design of the rational engineering rotors based on mathematical modeling, as they have been incorporated into the computer program. This program work is accomplished through a multi-step process which is shown in Fig. 6.

High mixing efficiency can be obtained when the best combination of dispersive mixing and distributive mixing is obtained. The stress field at the flight tip and circulation time were considered as mixing criteria.

The shear field at the flight tip was calculated by

$$\sigma_{TIP} = \eta_{TIP} \frac{U_{TIP}}{\delta} \quad (2)$$

**Fig. 5.** Flow diagram of rotor design

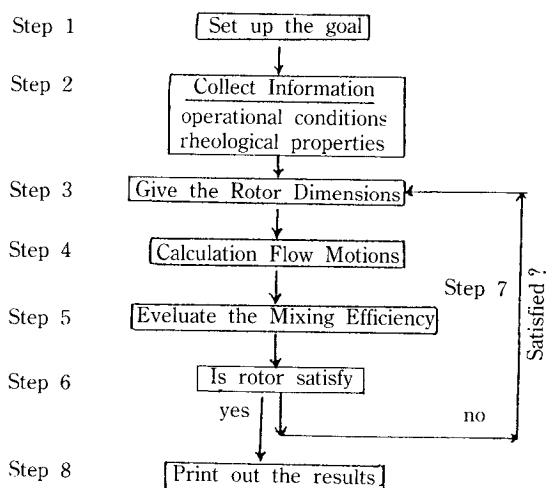


Fig. 6. Flow chart of rotor design

$$\eta_{TIP} = \frac{\eta_0}{1 + A \left(\frac{U_{TIP}}{\delta} \right)^{1-n}} \quad (3)$$

where σ_{TIP} ; shear stress at flight tip
 η_{TIP} ; viscosity at flight tip
 δ ; clearance between flight tip and chamber
 U_{TIP} ; velocity at flight tip
 C ; diameter of chamber
 U_{TIP} is defined as $\pi (c - \delta) \sin \theta$

The circulation time is defined as the time of the material starts at a certain position and return to the same position. Therefore,

$$t = A_L \left(\frac{1}{V_{L1}} + \frac{1}{V_{L2}} \right) \quad (4)$$

where A_L is axial length of chamber. V_{L1} and V_{L2} represent average velocities in axial direction of right side chamber and left side chamber, respectively. The calculated procedure of velocity fields was described in Appendix.

Example

Now we consider how to apply the computer program with an example. We use the following parameters in the example.

Table 2. Comparison of Properties between 5 rpm and 50 rpm

Rotor speed rpm	Flight Angle °	Stress Pa	Circulation time minutes
5	30°	4.1×10^5	2.4
	45°	3.8×10^5	2.0
	75°	2.9×10^5	4.1
50	30°	19.1×10^5	0.3
	45°	16.3×10^5	0.2
	75°	9.6×10^5	0.4

Rheological properties of the material

power index $n=0.3$

zero shear viscosity $\eta_0 = 10^5$ Pa.sec

experimental constant $A=0.3$

Geometrical parameters of the machine

clearance between rotor and chamber wall

$H=0.7$ cm

diameter of rotor $D=2$ cm

length of rotor $A_L=5$ cm

clearance between flight and chamber

$\delta=0.1$ cm

We operate the machine with rotor speeds of 5 and 50 rpm. In these conditions, we compare three different rotor designs with varied flight angle 30°, 45° and 75°. Table 2 summarizes the calculation results for non-Newtonian fluid. The circulation time is the lowest for 45° and stress field at the flight tip is the highest for 30°. The results indicate that the rotor with flight angle 45° makes the best distributive mixing and 30° for the best dispersive mixing. The rotor with flight angle 75° is the worst rotor design. As shown in Table 2, the flight angle for the double flights rotor is ranged from 15° to 45°. Therefore, the calculated result may be well agreed with those obtained from the literature.

We now examine how to determine the optimal operation condition. Fig. 7 shows the predicted shear stress and circulation time for non-Newtonian fluid as a function of rotor speed. If we choose a 30 degree flight angle rotor in processing with the same material ($n=0.3$, $\eta_0=10^5$ Pa.sec, $A=0.3$), we find a value around 40 rpm consid-

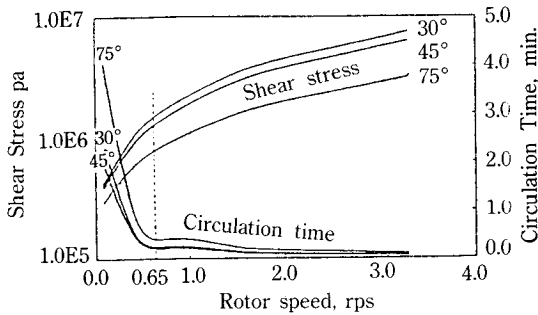


Fig. 7. Shear stress and circulation time vs. rotor speed

ring with the stress field and circulation time.

CAD enables finding the best rotor and optimum point without significant number of trial and adjustment. Therefore the increases in production efficiency reflected in cost reduction is possible with CAD.

Conclusion

The rational engineering rotors can be designed through CAD which represents a synthesis of various considerations. The program includes the material properties, operation conditions, and rotor dimensions. To evaluate the designed double flights rotors, the stress field at the flight tips and the circulation time were considered as mixing criteria. The shear stress at the flight tip increases with increasing rotor speed. However, the circulation time decreases dramatically with increasing rotor speed. The stress history at the flight tip represents a dispersive mixing ability. The circulation time is related to reorientation of flow and the flow motion induced distribution. The shorter circulation time makes for better distributive mixing. Therefore, the best combination of these factors would be used to design the rational engineering rotor. The authors believe that computer aided design enables the potential of considerable savings in terms of cost and time.

Appendix

A simple analytical model of flow in a twin non-

intermeshing pair of counter-rotating rotor internal mixer is considered. Here, we start with a single flight rotor and extend to double flights rotor. The helix angle θ is defined as the angle between screw flight on the rotor. Our intention is to formulate this problem in a manner similar to a modular screw extruder [18].

The flow is in two regions as

- I) between rotor and chamber wall
- II) between rotors

In a single flight rotor, the flow rate being moved along the screw channel can be expressed by

$$q = \frac{\pi D \Omega H}{2} \sin \theta \alpha_1 - \frac{H_3}{12\eta} \frac{\Delta P}{L} \alpha_2 \quad (5)$$

where α_1 and α_2 are correction functions because consideration of inter-rotor region. The functions are expressed by

$$\alpha_1 = \frac{4f}{3f+1} \quad (6-a)$$

$$\alpha_2 = \frac{4}{3f+1} \quad (6-b)$$

Let the f is defined as the fraction of the channel length which is in the neighborhood of the chamber wall

$$f = \frac{X_I}{X_I + X_{II}} \quad (7)$$

where I and II represent region I and region II, respectively. And L represents a helix length of the screw flight.

If rotor is completely surrounded by chamber, $f=1$, then coefficients $\alpha_1=\alpha_2=1$.

The viscosity function η is defined as mentioned previously.

$$\eta = \frac{\eta_p}{1 + A \left(\frac{R\Omega}{H} \right)^{1/n}} \quad (8)$$

Here, we assume that the two viscosity function of region I and region II exist in the internal mixer. We define the viscosity in regions I and II as η_I and η_{II} , respectively.

We may define a mean viscosity function as

$$\bar{\eta} = \eta_I f + \eta_{II} (1-f) \quad (9)$$

If we assume that $\eta_{II} \approx \eta_0$, then Eq. (9) can be expressed by

$$\bar{\eta} = \frac{\eta_0}{1+A \left(\frac{R\Omega}{H} \right)^{1-n}} f + \eta_0 (1+f) \quad (10)$$

The volume flow rate along the rotor axis is

$$Q_L = qW \cos\theta$$

$$= \frac{W}{2} \pi D H \Omega \sin\theta \cos\theta \alpha_1 - \frac{W H^3 \Delta P}{12 \bar{\eta} L} \cos\theta \alpha_2 \quad (11)$$

where W represents the channel width.

A double flights rotor is obtained by combining two sets of screw like flights having different flight angles. Let 'a' be the first flight and 'b' the second flight, then

$$q_a = \frac{\pi D \Omega \sin\theta_a H}{2} \alpha_1 - \frac{H^3}{12 \bar{\eta}} \frac{\Delta P_a}{L_a} \alpha_2 \quad (12)\text{-a}$$

$$q_b = \frac{\pi D \Omega \sin\theta_b H}{2} \alpha_1 - \frac{H^3}{12 \bar{\eta}} \frac{\Delta P_b}{L_b} \alpha_2 \quad (12)\text{-b}$$

Let L_a and L_b represent the length of flights, then total length of the flights is

$$L_D = L_a + L_b \quad (13)$$

and the total pressure is

$$\Delta P = \Delta P_a + \Delta P_b \quad (14)$$

From Eqs. (12) and (14), the flow rate is

$$q = \frac{\pi D \Omega H (L_a \sin\theta_a + L_b \sin\theta_b)}{2(L_a + L_b)} \alpha_1 - \frac{H^3}{12 \bar{\eta}} \frac{\Delta P}{L_a + L_b} \alpha_2 \quad (15)$$

If the two sets of flights on a double flights rotor are both forward and backward pumping and have equivalent angles ($\theta_a = -\theta_b = \theta$) and L_b is longer than L_a , then the flow rate is

$$q_L = \frac{\pi D \Omega H (L_a - L_b) \sin\theta \cos\theta}{2(L_a + L_b)} \alpha_1 - \frac{H^3 \Delta P}{12 \bar{\eta}} \frac{\cos\theta}{L_a + L_b} \alpha_2 \quad (16)$$

The velocity vector in axial direction of the rotor

is expressed by

$$V_L = \frac{q_L}{H} \quad (17)$$

Nomenclature

A	: Experimental constant
A_L	: Axial length of chamber
C	: Chamber diameter
D	: Rotor diameter
f	: Fraction of channel length
H	: Clearance between rotor and chamber
L	: Helix length of the screw flight
L_a, L_b	: Helix length of the first flight and the second flight
L_D	: Total helix length of the flights of the double flights rotor
L_a/L_b	: Relative length of the flights
n	: Power index
ΔP	: Pressure gradient
q	: Flow rate of the single screw flight
q_a, q_b	: Flow rate in 'a' 'b' set of the flight in the double flights rotor
q_L	: Longitudinal flow rate
Q_L	: Longitudinal volume flow rate
t	: Average circulation time
U	: Rotor speed
U_{TIP}	: Velocity at the flight tip
V_L	: Velocity in axial direction of the double flights rotor
V_{L1}	: Velocity in axial direction of the left side rotor
V_{L2}	: Velocity in axial direction of the right side rotor
W	: Channel width
X_I, X_{II}	: Channel length which is in the neighborhood of the channel wall of region I and region II

Greek Letters

η	: Shear viscosity
η_0	: Zero shear viscosity
η_{TIP}	: Shear viscosity at the flight tip
$\bar{\eta}$: Mean viscosity
σ_{TIP}	: Shear stress at the flight tip

- δ : Clearance between flight tip and chamber
 θ : Flight angle
 Δ : Distance between the flights
 α_1, α_2 : Correction functions
 Ω : Rotational speed

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