In-line Viscosity Fuzzy Control

SHIH-HSUAN CHIU, SHENG-HONG PONG

Department of Fiber and Polymer Engineering, National Taiwan University of Science and Technology, 43, Keelung Road, Section 4, Taipei, 10672, Taiwan, Republic of China

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ABSTRACT: A fuzzy control strategy on viscosity of a polymeric melt during the extruding processes is proposed to ensure producing the quality-consistent end products. Because the viscosity model in the control system varies with respect to different conditions of the system command (e.g., screw speed), we focus on using a fuzzy controller accomplished with a fuzzy modeling technique to solve the model-variant viscosity control system. Also, system stability analysis is presented. According to the simulation and the implementation results, better performances and a suitable using method are concluded. © 2000 John Wiley & Sons, Inc. J Appl Polym Sci 79: 1249–1255, 2001

Key words: fuzzy controller; fuzzy modeling; viscosity; in-line; extrusion

INTRODUCTION

In the polymer extrusion processes, the end-product quality would change in accordance with process variations. These process variations could result from the variations in the raw material (e.g., variations in regrind level,[1] drying conditions, and additive concentration, etc.) or in the performances of the molding machine and auxiliary equipment (e.g., signal fluctuation due to imprecise sensors and inconsistent machine operations, etc). An effective closed-loop control to eliminate process variations and to rapidly track the set point of quality factor is of primary importance.

Earlier studies performed quality control by off-line methods. Devices such as melt indexer and laboratory capillary rheometer[2] etc. were used to detect variations in flow characteristics and processibility of the polymer. Further steps of turning operation conditions were needed for control. Because the measurement took place away from the extrusion line, it would take not only more time and manpower but also wasted the material. Later, in the 1980s, the on-line rheometer[3] was used. Tests were performed by a bypass instrument in the extrusion line. However, from the viewpoint of real-time quality control, the significant signal delay resulting from the time required for melt to flow through the transit lines and the gear pump still existed. Recently, the in-line rheometer[4,5] was proposed, of which the flow characterization model provided is much more relevant to the extrusion process than the off-line data. Besides, it offers immediate cost saving by avoiding delays between product quality assessment, such as consistency.

Several studies have already worked on it. Kochher and Parnaby used stochastic techniques to obtain the dynamic model of the extrusion process.[6] Hassan and Parnaby used model-reference-optimal steady-state adaptive computer control[7] to achieve mass flow rate and product quality control. The mass flow rate was inferred from the die-inlet melt conditions of temperature and pressure. Screw speed, restrictor valve position, and temperature were treated as the manipulated variables. Wassick and Camp[8] designed a nonlin-

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Correspondence to: S.-H. Chiu (E-mail: schiu@p730.tx.ntust.edu.tw).

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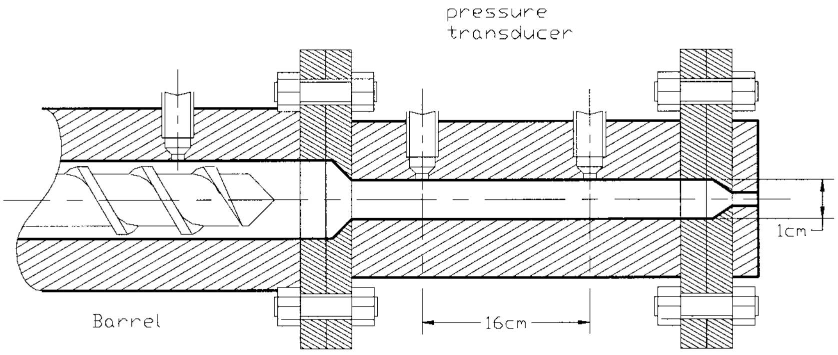


Figure 1 Schematic diagram of the in-line viscometer.

ear internal model controller for screw-torque control. The manipulated variable used to regulate the screw torque was the screw speed. A nonlinear dynamic model was developed related to the screw speed and screw torque. Ng et al.[9] designed a control strategy based on the discrete optimal regulator solution and included automatic dead-time compensation to perform pressure control by arranging the extruder gear pump. Chiu and Lin[10] used the minimum variance controller to reduce the melt-viscosity variations. Screw speed was treated as the manipulated variable. The system transfer function and the disturbance dynamic model of the plant were obtained experimentally. Other efforts on quality control in terms of temperature control can also be seen in the literatures, such as Dastych et al.,[11] Tsai and Lu,[12] Khalid et al.,[13] Pulkkinen et al.,[14] Taur and Tsai,[15] Omatu et al.,[16] etc.

We can draw some conclusions according to the studies mentioned above: (1) Mechanical, optical, electrical properties, and homogeneity, etc. cannot directly be measured in processing; process variables, such as die-pressure drop, flow rate, torque, viscosity, and temperature, etc., are generally taken as the quality characteristics. (2) The dynamic of the extrusion plant is a rather complex process that has led to a complicated dynamic model to ensure the polymeric melt with consistent properties.[10] These phenomena have resulted in the needs of complex modeling technique or control strategy.

On the demand of the efficient-achieving quality control in practical applications, Chiu and Pong[17] designed a fuzzy gain scheduled Proportional-Integral-Derivative (PID) controller to control the melt viscosity by manipulating the extruder screw speed. A second-order model related to the viscosity and the extruder screw speed is developed empirically to approximate the extrusion system to guarantee a stable fuzzy system.

In this study, we further develop a complete fuzzy control scheme in the viscosity control system. The fuzzy model of the viscosity system is also provided to approximate the complex and nonlinear system for stability analysis. Because a fuzzy controller provides a rather tolerance-permitted potential, we conclude that the fuzzy controller is suitable for applying the viscosity control system in the extrusion processes.

EXPERIMENTAL

Fuzzy Model Identification

Using fuzzy model to identify the viscosity control system, according to Pedrycz,[18] includes three main steps: determination of the structure of the model, estimation of the fuzzy relation of the fuzzy model, and validation of the model by testing its consistency with the data set. Before doing these, a set of input–output data pairs from the extrusion line was collected. The in-line viscometer[17] (as shown in Fig. 1) is used to measure viscosity continuously. The data sets of input–output pairs for low-density polyethylene (LDPE) at 180°C are listed in Table I. Both the input and output data are clustered into seven reference fuzzy sets as shown in Figures 2 and 3. The system shown in Figure 4 is governed by the following discrete time equation

$$X_{t+1} = X_t \bigcirc \Delta U_t \bigcirc R \tag{1}$$

where ΔU_t is a fuzzy set of control change at t time instant, X_t and X_{t+1} denote the fuzzy sets of the state of the process at t and $t + 1$ time

Table I Input–Output Data Sets of the Viscosity Control System

Input Screw Speed Change (rpm)	State Viscosity (Pa s)	Output Viscosity (Pa s)	Input Screw Speed Change (rpm)	State Viscosity (Pa s)	Output Viscosity (Pa s)
1.09	1320	1103	−0.49	1058	1072
1.25	1103	982	−0.84	1072	1094
2.49	982	824	−1.05	1094	1129
0.13	824	848	−1.08	1129	1176
2.06	848	815	−0.57	1176	1186
2.03	815	795	−1.27	1186	1241
1.69	795	820	0.18	1241	1228
2.02	820	802	−1.36	1228	1301
2.45	802	784	−0.68	1301	1321
0.09	784	793	−1.11	1321	1381
2.11	793	775	−0.77	1381	1420
1.83	775	768	−0.76	1420	1450
1.95	768	750	−0.85	1450	1501
1.03	750	756	−1.05	1501	1569
0.37	756	772	−0.81	1569	1622
0.1	772	784	−1.44	1622	1798
0.13	784	806	−0.75	1798	1872
−0.12	806	858	−0.94	1872	1965
−0.1	858	871	−0.86	1965	2139
−0.09	871	873	−0.35	2139	2130
0.16	873	960	−0.43	2130	2220
−0.19	960	968	−0.62	2220	2295
−0.93	968	998	−1.32	2295	2684
−0.09	998	994	−0.76	2684	28814
−1.02	994	1027	−0.14	28814	2765
−0.93	1027	1058	−0.08	2765	2627

instant, respectively, ○ is the min–max composition, R is the fuzzy relation which is calculated from the formula

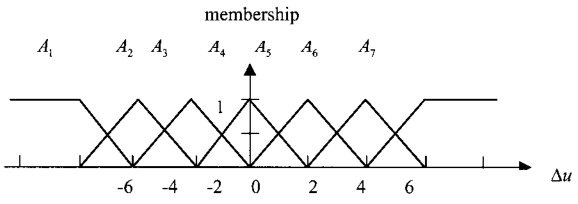


Figure 2 Fuzzy partition of the space ΔU.

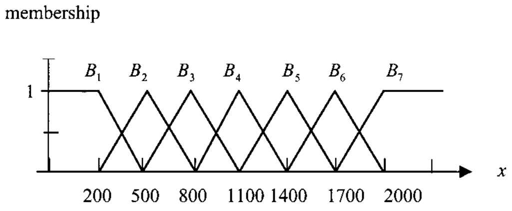


Figure 3 Fuzzy partition of the space X.

$$R = \bigcup_{t=1}^{n-1} (\Delta U_t \wedge X_t \wedge X_{t+1}) \tag{2}$$

where n is the number of data sets, and $\wedge$ represents taking the minimum of the respective sets. The fuzzy model output which was already derived in terms of the above algorithm and the experimental data for the viscosity control system is shown in Figure 5.

Fuzzy Controller

A typical diagram of the fuzzy control system with error and error change taken as the controller

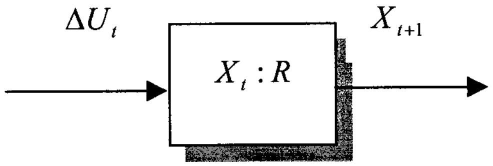
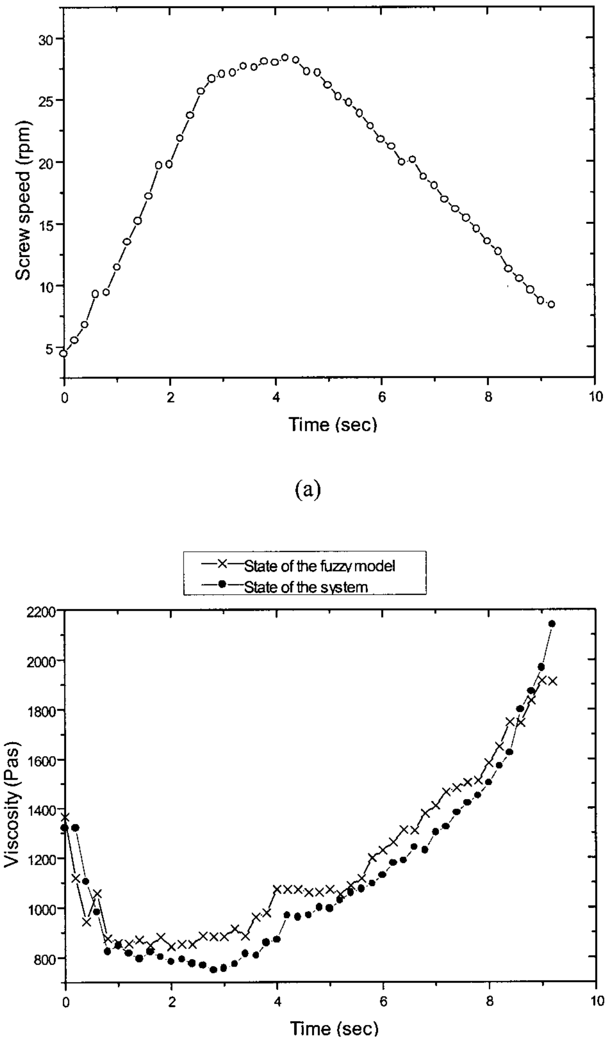


Figure 4 Open-loop process.



(a)

(b)

Figure 5 (a) Input of the fuzzy model and system. (b) Typical viscosity responses of the fuzzy model and system.

inputs is shown in Figure 6. Let R_E and $R_{\Delta E}$ represent the fuzzy relational matrix of the fuzzy controller inputs E and ΔE, respectively. The fuzzy control is obtained via a compositional rule of inference

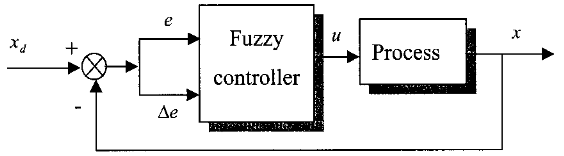


Figure 6 Block diagram of the fuzzy control system.

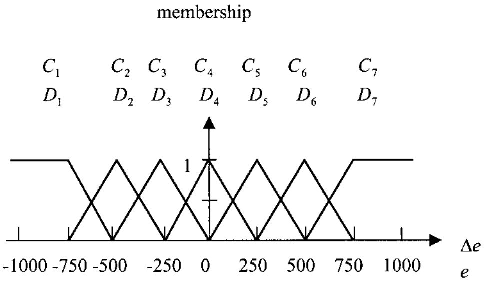


Figure 7 Fuzzy partition of the spaces E and ΔE.

$$\Delta U_t = (E_t \bigcirc R_E) \wedge (\Delta E_t \bigcirc R_{\Delta E}) \tag{3}$$

where E_t and ΔE_t stand for the fuzzy sets of error and error change, respectively. Also, seven inference fuzzy sets are assigned to cluster the inputs, as shown in Figure 7. The general control rules are described as

if error is E_t and error change is ΔE_t,
then control change is ΔU_t

According to Takagi and Sugeno,[19] the decision of 13 control rules can be made by referring to the partitions of the step response as shown in Figure 8. For example, the first partition needs a larger control change to achieve a short rising time. The control rules are presented in Table II. The additional rules in the table are designed to improve the rising time, overshoot, and the settling time. The values of the relational fuzzy set R_c are assigned as shown in Table III.

Stability Analysis

Kiska et al.[20] defined an energy function based on the total energy of a fuzzy system. It is stable if its

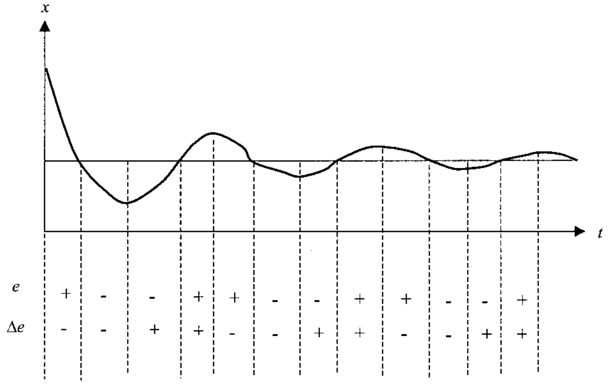


Figure 8 System step response.

Table II Fuzzy Control Rules

	Δe_k						
e_k	D_1	D_2	D_3	D_4	D_5	D_6	D_7
C_1				A_1	A_2		
C_2				A_2	A_3		
C_3			A_4	A_3	A_4	A_5	A_6
C_4	A_1	A_2	A_3	A_4	A_5	A_6	A_7
C_5	A_2	A_3	A_4	A_5	A_4		
C_6			A_5	A_6			
C_7			A_6	A_7			

total energy decreases monotonically until a state of equilibrium is reached. The energy function also takes into account several properties of the fuzzy membership functions such as the maximum, distribution, volume, and cardinality. To apply the energy function to the viscosity control system, the closed-loop equation of the fuzzy control system is derived. The substitution of the fuzzy control equation into the fuzzy process equation yields

$$\begin{aligned} X_{t+1} &= X_t \circ \Delta U_t \circ R \\ &= X_t \circ [(E_t \circ R_E) \wedge (\Delta E_t \circ R_{\Delta E})] \circ R \\ &= X_t \circ \{ \vee \{[(E_t \circ R_E) \wedge (\Delta E_t \circ R_{\Delta E})] \wedge R\}\} \qquad (4) \end{aligned}$$

where $\vee$ represents the maximum operation, and because the operators $\wedge$ and $\vee$ are distributive and commutative, we get

$$\begin{aligned} X_{t+1} & \\ &= X_t \circ \{ \vee \{[(E_t \circ R_E) \wedge R] \wedge [(\Delta E_t \circ R_{\Delta E}) \wedge R]\}\} \\ &= X_t \circ \{[(E_t \circ R_E) \circ R] \wedge [(\Delta E_t \circ R_{\Delta E}) \circ R]\} \qquad (5) \end{aligned}$$

To derive the free or unforced fuzzy dynamic system, we define the two input fuzzy sets E_0 and ΔE_0 with the membership functions

$$\mu_E(e) = \begin{cases} 1, & e = 0 \\ 0, & \text{otherwise} \end{cases} \qquad (6)$$

$$\mu_{\Delta E}(\Delta e) = \begin{cases} 1, & \Delta e = 0 \\ 0, & \text{otherwise} \end{cases} \qquad (7)$$

Let

$$P_E = E_0 \circ (R_E \circ R) \qquad (8)$$

$$P_{\Delta E} = \Delta E_0 \circ (R_{\Delta E} \circ R) \qquad (9)$$

$$P = P_E \wedge P_{\Delta E} \qquad (10)$$

then the closed loop fuzzy control equation has the form

$$X_{t+1} = X_t \circ P \qquad (11)$$

For convenience, we write the equation as

$$Y_t = X_t \circ P \qquad (12)$$

The energy function is defined as

$$\text{Energy} = \left(\frac{1}{mn}\right) \sum_{i=1}^{n} \sum_{j=1}^{m} w(x_i, y_j) f(\mu_P(x_i, y_j)) \qquad (13)$$

where m and n stand for the cardinality of X and Y, $w(x_i, y_j)$ is a function denoting the position on the fuzzy membership set, and $f(\mu_P(x_i, y_j))$ is a function of the membership value. According to Kiszka and Gupta,[20] the system is stable, because its energy converges to a value of 0.571.

RESULTS AND DISCUSSION

The control system is practically implemented on the LDPE extrusion process. The temperature is set at 180°C. The specifications of the single screw extruder are shown in Table IV. The extruder is equipped with five pressure transducers that are combined with temperature sensors. Three of them (Asahi Model TTJ-N67A) are located, respectively, at the solid polymer transition, the molten transition section, and the melt transition

Table III The Relational Fuzzy Set R_c

E, ΔE	ΔU					
0.50	0.50					
	0.50	0.50				
		0.25	0.25	0.25	0.25	
0.15	0.15	0.15	0.10	0.15	0.15	0.15
	0.25	0.25	0.25	0.25		
			0.50	0.50		
					0.50	0.50

Table IV Specifications of the Single Screw Extruder

Specification	Value
Screw diameter (mm)	45
L/D ratio	25
Compression ratio	3.37
Production output rate (kg/h)	4–35
Screw speed (rpm)	0–100

Table V Approximate Performances of Controllers on the Viscosity Control System

	Fuzzy Controller	Zeigler–Nichols Tuned PID
Overshoot (Pa s)	70	150
Setting time (s) (with respect to 5% deviation from the setpoint)	5.0	7.5

section; the rest (Dynisco Model TPT4636) are located at the die, as shown in Figure 1. A personal computer combined with analog-to-digital (A/D) and digital-to-analog (D/A) converters (Axiom Model AX5411) and RS232 interface is used for monitoring and controlling all of the process information from the extruder including temperature, pressure, and screw speed. All of the data acquisition and display software, including the process control algorithms, is written in C programming language.

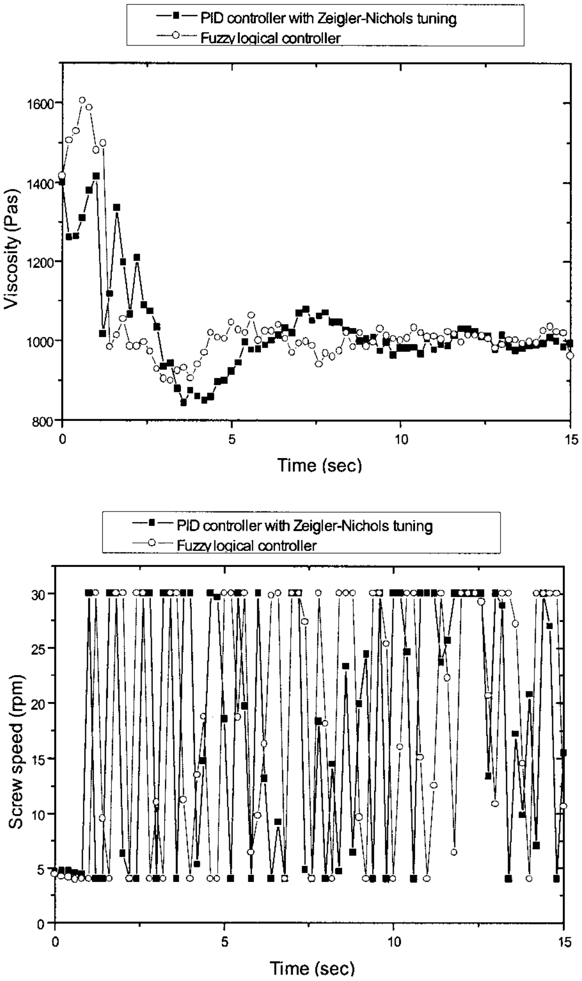


Figure 9 (a) Process output for fuzzy controller. (b) Controller output for fuzzy controller.

Figure 9 shows a typical measured output and controller output based on the fuzzy controller for a set point of 1000 Pa s. The result of a PID controller with Zeigler–Nichols tuning[21] is also presented for comparison. The performances of both controllers are shown in Table V. In the table, shorter rising time, smaller overshoot, and shorter settling time is achieved by using the fuzzy controller. Besides, the viscosity fluctuation problem that Chiu and Pong[17] mentioned has been conquered by using an independent power supply for the pressure transducers and smaller scale pressure transducers.

CONCLUSION

This article presents the fuzzy control scheme to continuously produce polymers with desired viscosity in an extrusion molding process. On the basis of the results reported in this article, it is concluded that the melt viscosity can be properly controlled by the proposed method with better performances. The advantages of using the fuzzy controller on the in-line viscosity control also embrace that it has become an easily achieved control task in comparison to other control strategies.

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