中國機械工程學刊第四十一卷第六期第 773~780 頁(民國一百零九年)
Journal of the Chinese Society of Mechanical Engineers, Vol.41, No.6, pp.773~780 (2020)

Temperature Control of a Plastic Injection Molding Machine Using Closed-loop Control Based on System Identification

Peeraya Pongpanyaporn*, Chin-Wen Lin* and Yong-Lin Kuo**

Keywords : plastic injection molding machine, system identification, temperature control.

ABSTRACT

The temperature control of injection machines is generally achieved by using an auto-tuning PID controller. However, auto-tuning may not meet the industrial demands in some situations. Therefore, it is necessary to switch to manual adjustment, but it will take more time and use more plastic materials. This paper presents a temperature controller design of a plastic injection molding machine by constructing a closed-loop feedback control system based on system identification. System identification treats a system as a black box. By conducting an experiment to record the input and output data, a mathematical model of the system can be obtained. Therefore, based on the model, the system can be systematically analyzed, and the dynamical characteristics can be obtained. Furthermore, the model can be used to predict and validate other experimental results. In this study, first of all, the mathematical model of the machine is established through a system identification experiment to collect input and output data of the machine and then the software Matlab System Identification Toolbox used to evaluate the model. Secondly, based on the established model, a PID controller is designed based on the Ziegler-Nichols tuning method, and the numerical simulations are performed in order to satisfy the requirements of the machine. Finally, some experiments are conducted so as to validate the controller, and the results show that the temperature control performance meets the requirements of the machine.

Paper Received June, 2020. Revised Sepfember, 2020. Accepted November, 2020. Author for Correspondence:Yong-Lin Kuo.

* *Graduate Student, Graduate Institute of Automation and Control, National Taiwan University of Science and Technology, Taipei, Taiwan 106, ROC.*

** *Associate Professor, Graduate Institute of Automation and Control, National Taiwan University of Science and Technology, Taipei, Taiwan 106, ROC.*

INTRODUCTION

A plastic injection molding machine is a machine to produce molded products by injecting molten plastic materials by heating devices into a mold and then cooling and solidifying the products. The machine is divided into two units, a clamping unit and an injection unit, where the clamping unit is used to open and close a die, and the injection unit is used to melt plastic by heating and then to inject molten plastic into a mold.

Temperature control is an important issue in a plastic injection molding machine, because molding quality is affected by temperature control performance. The main control challenges for such processes are to avoid overheating, which refers to temperature overshoot, in the heating stage and to tightly maintain the set-point temperature against load disturbances and process/environmental variations. Furthermore, thermal processes typically have slow time constants and long time delay, causing difficulties to control-system design (Huzmezan et al., 2002). Dubay (2002) applied a generic learning and self-optimizing MPC method to control melt temperature of injection molding machine. Juang et al. (2006) applied a TSK-type recurrent fuzzy network control to molding process, where the control is characterized by its recurrent structure, on-line structure and parameter learning. Gerber et al. (2006) presented a method of coupling computational fluid dynamics to model predictive control for controlling melt temperature based on a model obtained through open-loop testing. Jang (2007) presented cascade type simple PI controller with input limitation to tackle with the change of barrel temperature along the whole operating process. Yao et al. (2008) presented a control scheme by combining a feedback controller and an iterative learning feedforward controller, where the molding process is controlled by generalized predictive control feedback during the idle state and then is switched to operation by using the feedforward control scheme adding a compensation signal learned from the last run of the operation. Zhou (2008) presented a fuzzy linear control design method with trapezoidal membership function for fuzzification to control the temperature of an injection molding machine using Simulink, Matlab to simulate the controller and obtain the fuzzy parameters. Liu et al. (2009) presented two identification methods which are the methods based on step response to obtain the heat-up model and based on a relay test around the set-point temperature to obtain the model stable in order to reject load disturbances. Lu et al. (2010) presented a neural-network-based predictive control scheme for a plastic injection molding process, which is a discrete-time multi-input multi-output system and is modeled by a recurrent neural network, where an adaptive learning rate approach is used to estimate the model parameters. Peng et al. (2012) presented a nonlinear model predictive control based on diagonal recurrent neural network control multi-section barrel melt temperatures of an injection molding machine, where genetic algorithm is used as a rolling optimization tool. Prasad et al. (2012) proposed a control scheme for the barrel temperature control in injection molding machine, where the scheme is an I-PD controller, a modified form of PID to reduce the undesirable overshoot, and particle swarm is used to optimize the controller to gain the reductions of settling time and peak overshoot. Zhang et al. (2013) presented a fuzzy adaptive PID control for the multi-channel temperature control system of injection molding machine. Tsai (2015) presented an adaptive decoupling predictive temperature control using neural networks (NN) for extrusion barrels in plastic injection molding machines, where the extrusion barrels are approximated by decoupling linear system models together with independent NN models. Kanagalakshmi et al. (2016) proposed a multi-model for injection molding process, which is controlled by PID, fuzzy, and adaptive neuro fuzzy inference system (ANFIS) control schemes. De Meo et al. (2018) developed a system to dynamically control the local temperature of the cavity surfaces in microinjection molding, where the system is used to investigate the effects of rapid variations of the temperature of a 200 μm thick cavity on the reachable flow length and study the morphology of microinjection molded parts of poly.

In review of literature, there are a limited number of papers addressing both system identification and temperature control of molding process. This study investigates a four-channel molding machine, where the system identifications of the four channels are preformed first, and then PID control with an anti-windup scheme are applied to the four channels. Numerical simulation and experimental work are conducted for validation.

The rest of this paper is organized as follows. Section 2 presents the system identification of the machine. Section 3 presents control design and numerical simulations. Section 4 presents experimental results. Section 5 presents the significant conclusions.

SYSTEM IDENTIFICATION OF PLASTIC MOLDING INJECTION MACHINE

In order to produce a plastic molded product, the process starts in an injection unit. Firstly, a granulated plastic is filled into a hopper. After that, screw feeds granulated plastic through heaters in order to melt it and inject molten plastic to a mold which has coolant. Finally, the molten plastic is solidified and released from the machine by a clamping unit.

This study only focuses on temperature control in the injection unit. The injection unit of an injection molding machine is shown in Figure 1. The heating chamber has four channels, and each channel consist of a thermocouple sensor and a heater, where the heaters are driven based on a PWM signal.

System identification is an approach to determine a dynamics model of a system that has no more or less mathematical description based on prior knowledge, objectives, and observed data from an experiment (Keesman, 2011). The process of system identification is shown in Figure 2.

To simplify the modeling of the injection unit, each channel is modeled as a system, where the input and output are the PWM signal and the temperature, respectively.

To perform the system identification, an experiment is conducted to obtain the input and output signals. The input signal is assigned as a seven-stair function shown in Figure 3(a), and the temperatures of the four channels are shown in Fig. 3(b). The transfer function of the system is considered to include two poles, one zeros and one time-delay, which is expressed as

$$G(s) = \frac{K(1+T_z s)e^{-T_d s}}{(1+T_{p1}s)(1+T_{p2}s)} \tag{1}$$

where K is the DC gain;, T_z, T_{p1}, and T_{p2} the time constants referring to the zero and the two poles, respectively; T_d is the delay time. All parameters are unknown to be determined by utilizing the software Matlab System Identification Toolbox, and the results are obtained and listed in Table 1. Table 2 shows the best fitness, and the results show that the four models reach over 95% fitness.

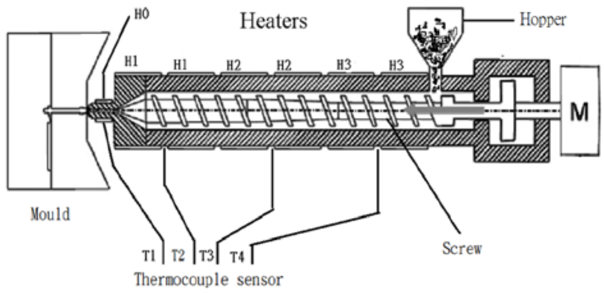


Fig. 1. Injection unit of an injection molding machine

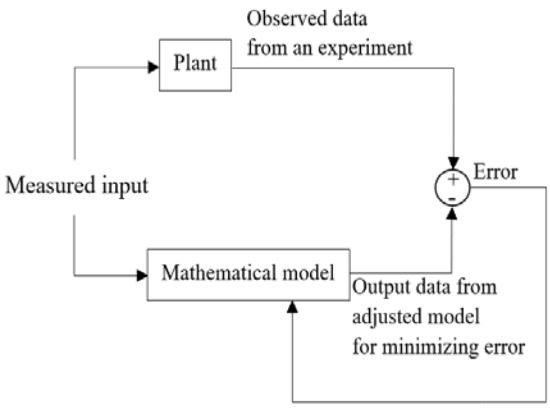


Fig. 2. System Identification process diagram

Table 1. Model parameters of the four channels

	Channel 1	Channel 2	Channel 3	Channel 4
K	19.4683	17.3215	15.5429	14.8441
T_{p1}	12782.6504	8652.2994	7994.899	21156.1995
T_{p2}	1139.2284	124.564	286.0729	133.8454
T_z	1959.0635	53.1456	192.3339	5025.034
T_d	21.4204	0	18.1339	0

Table 2. Best fitness of system identification

	Channel 1	Channel 2	Channel 3	Channel 4
Best fitness (%)	98.64	98.23	97.97	95.37

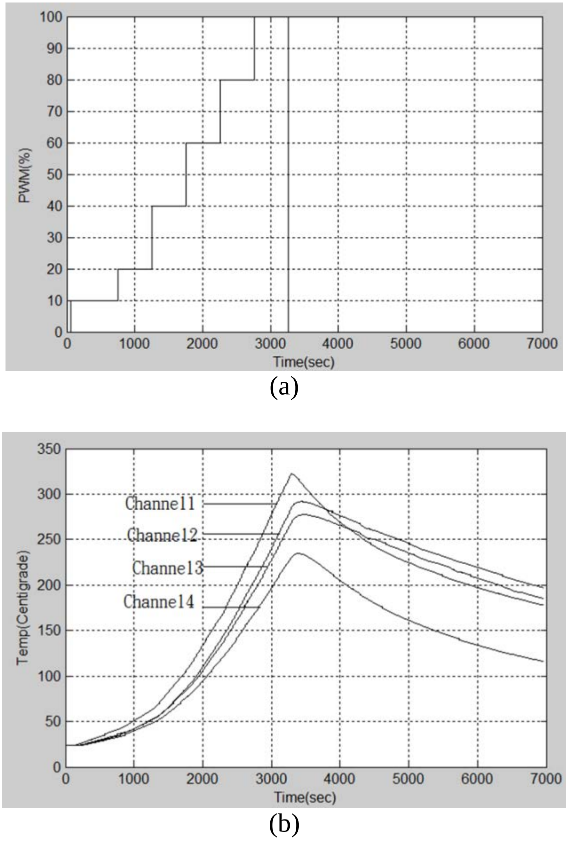


Fig. 3. (a) Input signal and (b) output signals for system identification

PID CONTROL AND SIMULATIONS

PID controller is a form of feedback. P-term stands for proportional to the error, I-term stands for proportional to the integral of the error and D-term stands for proportional to the derivative of the error. These 3 terms are summed together in order to obtain the control signal described by

$$u(t) = K_P\left(e(t)+\frac{1}{T_I}\int_0^t e(\tau)d\tau + T_D\frac{de(t)}{dt}\right) \qquad (2)$$

where u is a control signal; e is an error between reference and current output; K_P is the proportional gain; T_I and T_D are the integral time and the derivative time, respectively (Astrom, 2002).

Ziegler-Nichols method is a popular method for tuning the PID controller. To determine the values of K_P, T_I and T_D, the integral gain and derivative gain are set as zero then the proportional gain is increased until the output signal oscillate with the constant amplitude. The obtained proportional gain defined as the ultimate gain K_u and the period of oscillation defined as P_u. After that, K_P, T_I and T_D values are obtained as Table 3 (Chidambaram et al., 2018).

Anti-windup is used to prevent integration wind-up in PID controller when the actuator is saturated. There are many methods can be applied such as Setpoint Limitation, Incremental Algorithms and Back-Calculation and Tracking. As for the Setpoint Limitation, the output signal is not reached the actuator limit because the setpoint variation is limited. However, the performance of the controller will be poor and it cannot prevent the windup from disturbances. As for the Incremental Algorithms, the rate of change of the control signal is added to an integrator term until the output signal is saturated. This method is called velocity algorithm and the result is equivalent to Back-Calculation and Tracking. Nevertheless, Back-Calculation and Tracking provides better performance while the noises are considered (Silva et al., 2018). Moreover, the integrator term is reset dynamically with time constant in Back-Calculation and Tracking and the method has no any effects to the control signal in the state without saturation (Astrom, 2002).

In this study, only Back-Calculation and Tracking is applied. The block diagram of PID control with anti-windup based on Back-Calculation and Tracking is presented in Figure 4. By this method, the controller resets synchronously with a time constant T_t and the study suggests to design T_t as

$$T_t=\sqrt{T_I T_D} \tag{3}$$

Table 3. Ziegler–Nichols methods parameters

Controller	K_P	T_I	T_D
P	$0.5K_u$	-	-
PI	$0.45K_u$	$P_u/1.2$	-
PID	$0.6K_u$	$P_u/2$	$P_u/8$

This study applies a PID control to track the desired chamber temperature, where the controller gains are obtained by using the Ziegler-Nichols (Z-N) PID tuning method. After obtaining the controller gains, one fine-tunes the gains in order to have better control performances based on numerical simulations of the closed-loop control. Besides, the back-calculation anti-windup method is applied (Astrom et al., 2006) Table 4 list the PID gains for each channel.

Table 4. PID controller gains

Channel	K_P	K_I	K_D
CH1	10	0.1	100
CH2	20	0.1	100
CH3	18	0.1	100
CH4	40	0.2	200

EXPERIMENTAL RESULTS

The experimental setup for the temperature control of the machine is illustrated in Figure 6, where a temperature controller is used to regulate the chamber temperatures. Besides, a PID controller is executed in a notebook computer, and its USB port is connected to the controller's RS-232 port through a port converter to receive the sensor data and to transmit PWM signals. The specifications of the controller and other components using in the experiment is shown in Table 5.

The requirements of the temperature control are listed as:

- The desired temperature is 250°C.
- The overshoot is less than 4°C.
- The steady state error is within ±1°C.

One performs an experiment to demonstrate the chamber temperature to reach the desired temperature 250°C based on aforementioned controller design. The simulation block diagram is shown in Figure 7, and the simulation results are shown in Figure 5. For the experiments, the results are shown in Figure 8. The results show that the temperatures of the four channels reach 250°C around at 2,000 seconds, and there are slight oscillations at steady state.

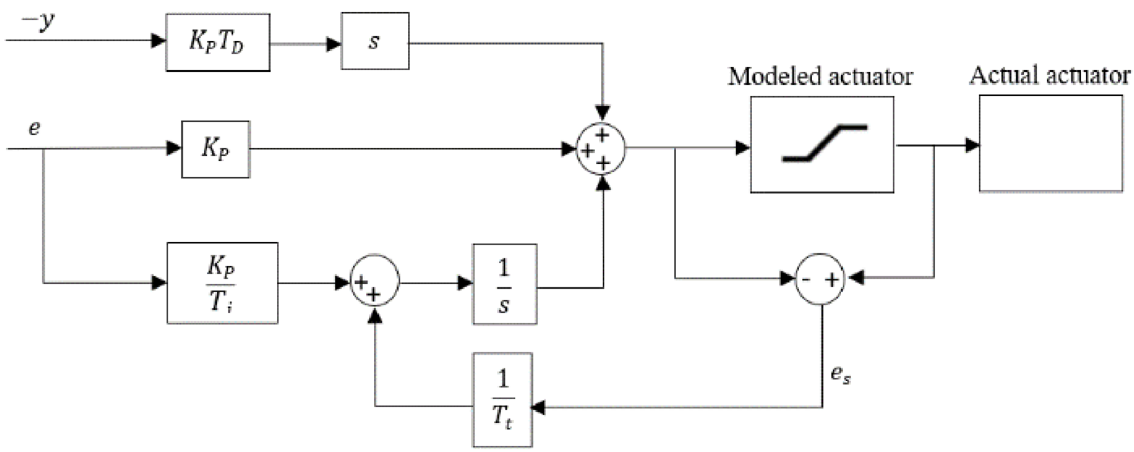
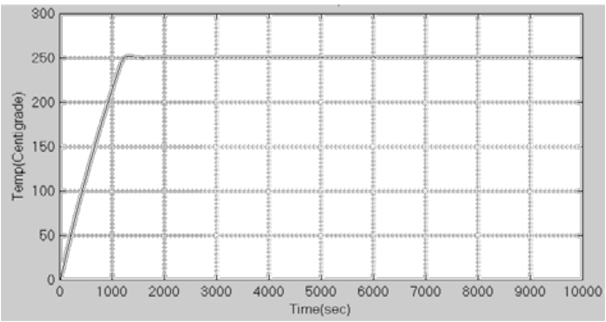


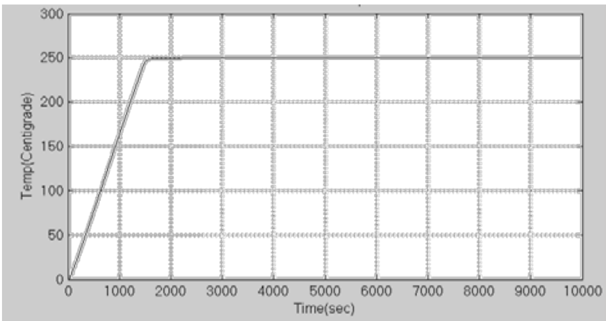
Fig. 4. PID control with anti-windup based on Back Calculation and Tracking diagram

Table 5. The specifications of the controller and other components using in the experiment

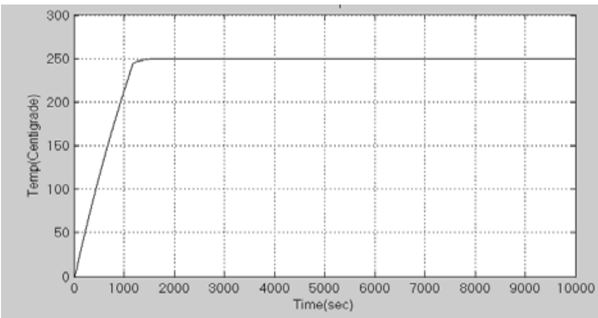
Processor	• MCU : 16bit fixpoint Digital signal processor
Data converter	• A/D : Dual slop analog to digital converter (sample rate 30/sec) • A/D Sample rate channel /1 sec (Ts=1sec) 12Bits resolution • Voltage REF : 2.048V
Sensor & Amplifier	• K-type Thermocouple sensor : out voltage ≈40uV/℃ • Sensor output voltage after amplifier 40 uV x 100 = 4 mV /℃ • Op amp : TI(texas instrument) INA128 (gain = 100)
Output control	• Device : 220V/40A SSR(solid state relay) • PWM width : 2000ms x percentage (100% = 2000msec) • PWM counting clock (resolution): 1msec
Specifications	• Full scale voltage 2.048V/4mV = 501.2 ≈ 500℃ • 1℃= 4mV 1 count of A/D converter value = 0.25 ℃



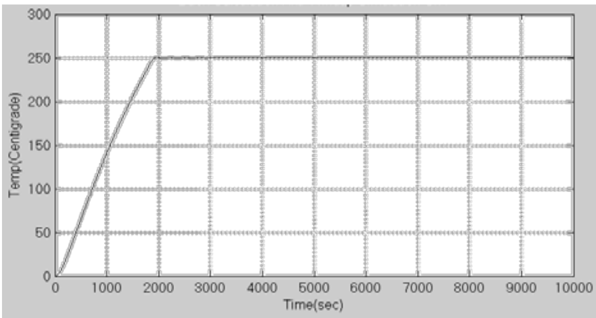
(a)



(c)



(b)



(d)

Fig. 5. Temperature responses from simulation for (a) channel 1, (b) channel 2, (c) channel 3 and (d) channel 4

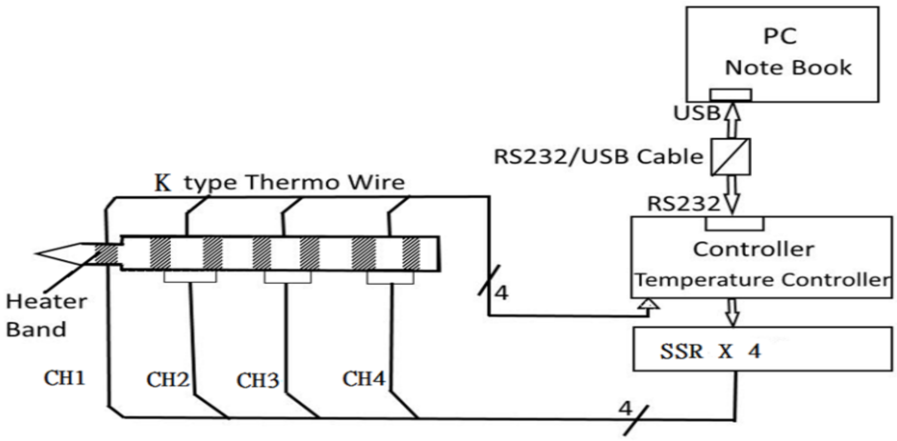


Fig. 6. Hardware-in-the-loop of temperature control

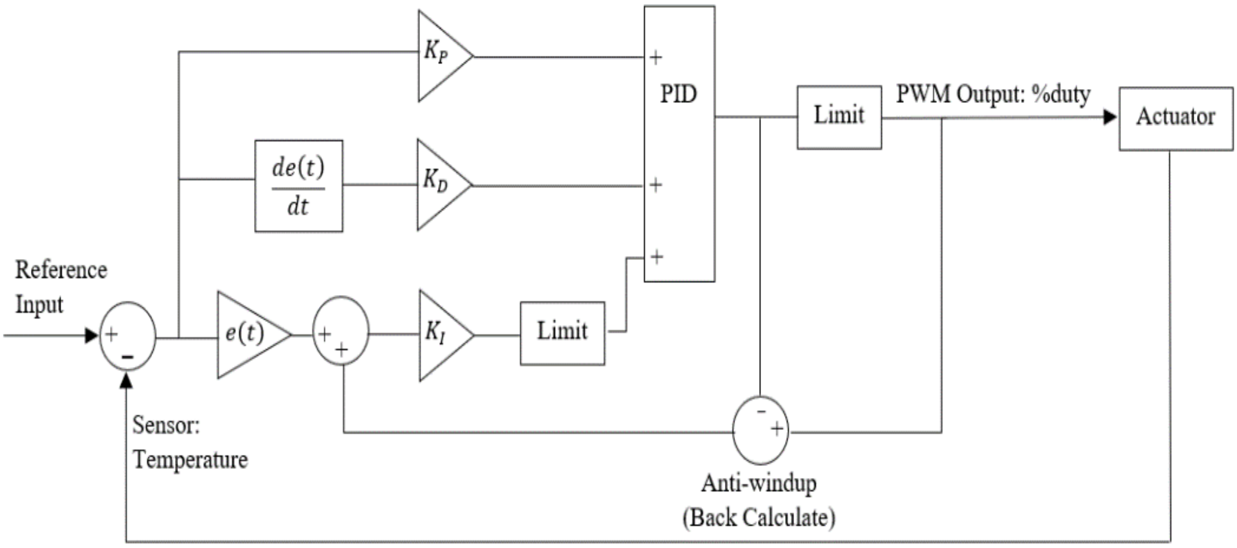


Fig. 7. Temperature control software diagram

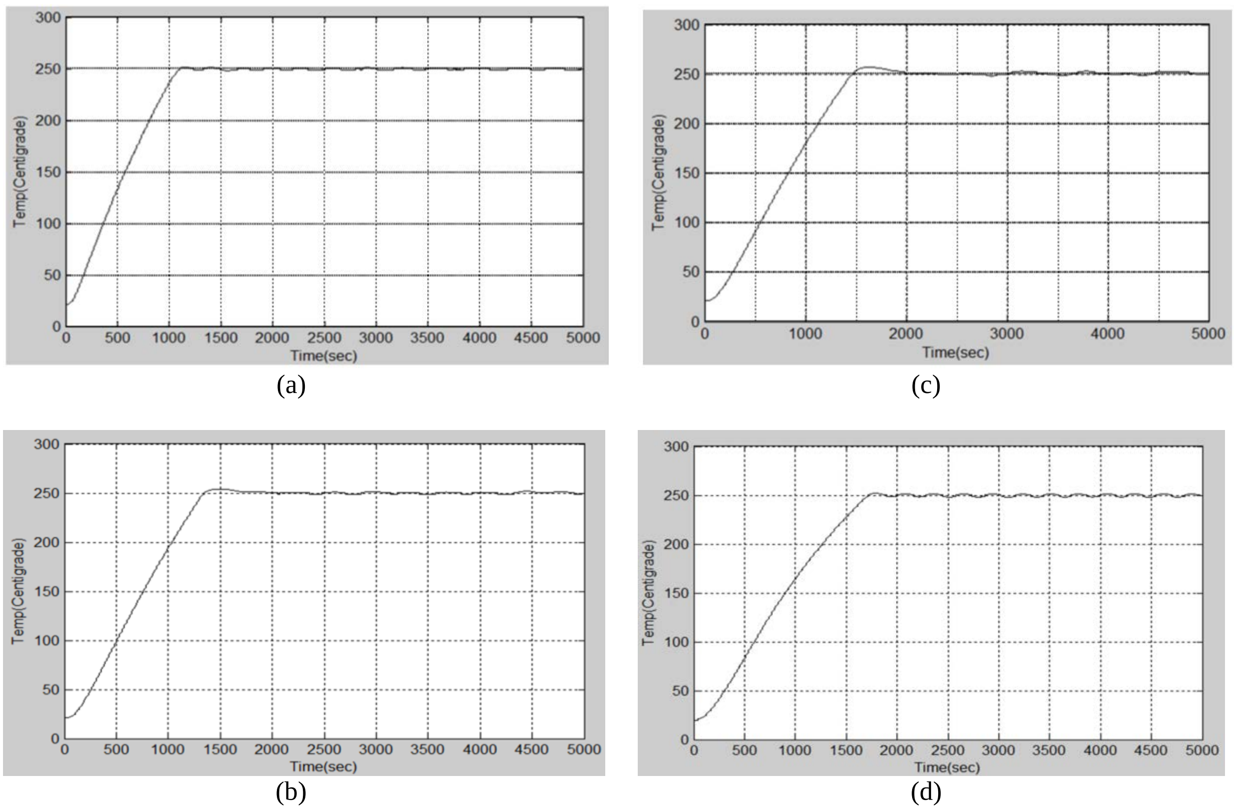


Fig. 8. Temperature responses of experiment for (a) channel 1, (b) channel 2, (c) channel 3 and (d) channel 4

CONCLUSIONS

This paper presents system identification and temperature control of an injection molding machine. The investigated machine has four channels in the injection unit, and each channel consists of a thermocouple sensor and a heater. Besides, each channel is modeled as a system, and its transfer function composes a zero, two poles, and a time-delay. One conducts an experiment to collect the input and output data, and then the software Matlab System Identification Toolbox is used to identify the parameters in the transfer functions. Furthermore, a PID controller with anti-windup is applied to perform the closed-loop control simulations, where the controller parameters are obtained through the Z-N tuning method. Also, the parameters are fine-tuned in order to obtain better performances based on simulation results. Finally, the designed controllers are applied to experiments, and the experimental results show that the desired temperature can be reached after 2,000 seconds, and the steady-state temperate is kept with only slight oscillations.

ACKNOWLEDGMENT

This study was supported in part by the Ministry of Science and Technology, Taiwan, under Grant MOST 107-2221-E-011-135.

REFERENCE

Astrom K.J. and Hagglung T., *Advanced PID Control*, ISA - The Instrumentation, Systems and Automation Society (2006).

Astrom K.J., "Control System Design", Lecture note, Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, USA (2002).

Chidambaram M. and Saxena N., *Relay Tuning of PID Controllers For Unstable MIMO Processes*, Springer Nature, Singapore (2018).

Dubay R., "Self-optimizing MPC of melt temperature in injection moulding", *ISA Trans.*, Vol. 41, pp.81-94 (2002).

Gerber A.G., Dubay R., and Healy A., "CFD-based predictive control of melt temperature in plastic injection molding", *Appl. Math. Model.*, Vol. 30, pp.884-903 (2006).

Huzmezan M., Gough W.A., Dumont G.A., and Kovac S., "Time delay integrating systems: A challenge for process control industries. A practical solution", *Control Eng. Pract.*, Vol. 10, pp.1153-1161 (2002).

Jang Y.J, "Temperature Control of Injection Molding Machine using PI Controller with Input Restriction", *J. Korean Inst. Electr. Electron. Mater. Eng.*, Vol. 56, pp. 604-610 (2007).

Juang C.F., Huang S.T., and Duh F.B., "Mold temperature control of a rubber injection molding machine by TSK-type recurrent neural fuzzy network", *Neurocomputing*, Vol. 70, pp.559-567 (2006).

Kanagalakshmi S., Manamalli D., and Mohamedrafiq M., "Implementation of multimodel-based PID and intelligent controller for simulated and real-time temperature control of injection molding machine", *Chem. Eng. Comm.*, Vol. 203, pp.452-462 (2016).

Keesman Karel J., *System Identification: An Introduction*, Springer-Verlag, London (2011).

Liu T., Yao K., and Gao F., "Identification and Autotuning of Temperature-Control", *IEEE. T. Contr. Syst. T.*, Vol. 17, pp.1282-1294 (2009).

Lu C.H., Tsai C.C., Liu C.M., and Charng Y.H., "Neural-network-based predictive controller design: An application to temperature control of a plastic injection molding process", *Asian J. Control*, Vol. 12, pp.680-691 (2010).

Meo A. D., Santis F.D., and Pantani R., "Dynamic local temperature control in micro-injection molding: Effects on poly (lactic acid) morphology", *Polym. Eng. Sci.*, Vol. 58, pp.586-591 (2018).

Peng Y., Wei W., and Wang J., "Model predictive synchronous control of barrel temperature for injection molding machine based on diagonal recurrent neural networks", *Mater. Manuf. Process.*, Vol. 28, pp.24-30 (2012).

Prasad S.S. and Balakrishnan P.A., "PSO based I-PD controller for barrel temperature control in plastic injection molding system", *Eur. J. Sci. Res.*, Vol. 80, pp.351-357 (2012).

Silva L.R., Flesch R.C.C., and Normey-Rico J.E., "Analysis of Anti-windup Techniques in PID Control of Processes with Measurement Noise", *IFAC-PapersOnLine*, Vol. 51, pp.948-953 (2018).

Tsai C.C. and Lu C.H., "Adaptive decoupling predictive temperature control using neural networks for extrusion barrels in plastic injection molding Machines", Conf. Proc. *IEEE Int. Conf. Syst. Man. Cybern.*, Kowloon, China (2015).

Yao K., Gao F., and Allgöwer F., "Barrel temperature control during operation transition in injection molding", *Control Eng. Pract.*, Vol. 16, pp.1259-1264 (2008).

Zhang Y. and Mo W., "The algorithm of fuzzy adaptive PID control applied to the multi-channel temperature control system of the injection molding machine", *Appl. Mech. Mater.*, Vols. 336-338, pp.826-832 (2013).

Zhou H.F., "Simulation on Temperature Fuzzy Control in Injection Mould Machine by Simulink", *ICNSC*, Sanya, China (2008)

利用基於系統識別的閉迴路控制實現塑膠射出成型機之溫度控制

李玉芬　　林慶文　　郭永麟
國立臺灣科技大學自動化及控制研究所

摘 要

射出成型機的溫度控制通常是利用參數自動調節的 PID 控制器來實現。但是在某些情況下，自動調節可能無法滿足工業上的需求。因此有必要切換到手動調整，但是這將花費更多的時間並使用更多的塑料。本篇論文提出建構一個基於系統辨識的閉迴路反饋控制系統以實現塑膠射出成型機的溫度控制器設計。系統識別是將系統視為一個黑盒子，藉由實驗記錄黑盒子的輸入和輸出數據，可以獲得系統的數學模型。因此，基於該模型，可以對系統進行系統分析，並獲得動力學特性。此外，該模型可用於預測和驗證其他實驗結果。在本研究中，首先利用系統識別實驗來蒐集塑膠射出成型機的的輸入和輸出數據，再利用 Matlab 軟體的系統識別工具箱來計算書學模型，其次基於所建立的模型，利用 Ziegler-Nichols 調整方法設計 PID 控制器的參數，並進行整個閉迴路系統的數值模擬，期望滿足該射出射出成型機的性能需求，最後進行了實驗以驗證所設計的控制器的，而且實驗結果顯示溫度控制性能符合射出成型機的性能要求。