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Original Article

Optimized parameters to tune I-PD control through firefly algorithm for heating operations of plastic injection molding

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Abstract

This research presents firefly algorithm optimization tuned integral plus proportional and derivative (I-PD) controller to control the temperature response model according to Tao Liu and Ke Yao and Furong Gao model. In order to achieve effective and efficient control, proportional integral and derivative (PID) controller is used to compare with I-PD controller through using Ziegler-Nichols Tuning (ZN), particle swam optimization (PSO), and fuzzy logic controller compared with firefly algorithm optimization for tuning. All controller designs are modeled in SIMULINK and empirical tests. From the results, it is practically observed that firefly algorithm tuned PID and I-PD controller outperforms other controllers named ZN, PSO controllers, and also fuzzy logic controller. In addition, firefly algorithm optimization method provides a good performance as overshoot reduction and settling. In conclusion, firefly algorithm is a suitable tuning method for temperature controller and can save settling time and reduce overshoots of input power.

Keywords: firefly algorithm optimization, integral plus proportional and derivative (I-PD) controller, proportional integral and derivative (PID), Ziegler-Nichols Tuning (ZN)

1. Introduction

Most commonly electric utilities are controlled by convenient controllers such as proportional plus integral (PI), and proportional plus integral plus derivative (PID). Many researchers have tried to obtain the better efficiency on the good output that matches the set point of machine parameters. For example, there was the usage of a digital signal processor (DSP)-based PID to cope with heating plastic injection mold (Jeong *et al.*, 2015). This research provided optimal methodology of DSP-based PID to determine the temperature distribution of injection mold and tried to lead to the smallest gradient temperature mold and the minimum cooling time. Also at the same year, there was the development of temperature controller in plastic extrusion system. Results showed four control techniques being PI-PID, two intelligent controller FUZZY and ANFIS that provided good performances especially ANFIS controller (Mahto & Murmu, 2015). Another research used a control system of temperature for injection molding machine through PID neural networks. This research concluded that PID with neural network method could handle better a convenient PID under the occurrence of large fluctuation and vibration in temperature (He & Shi, 2015). There was also the investigation on the control system of temperature for injection molding machine by using fuzzy logic control to compare with the traditional PID controller. The results illustrated that fuzzy logic control could reduce a settling time and overshoot of temperature set-point (Agrawal & Gupta, 2016). Moreover, some researchers also used a class of evaluation algorithm optimization methods. For instance, there was not only implementation of the multi objective particle swarm optimization (MOPSO) to control gantry crane

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system via PID and PD controller (JAAFAR *et al.*, 2014) but also the usage of the genetic algorithm (GA) to work with PID controller (Amanullah & Tiwari, 2014). Results of both researches provided a good performance which lead to the reduction of overshoot and the shortest settling time. Likewise, firefly algorithm (FA) that had been created since particle swarm optimization and genetic algorithm (GA) was employed to seek optimal parameters of PID controller, such as some researches indicated a good controlled performance of firefly algorithm (FA) (Naidu, Mokhlis, & Bakar, 2013) and (Kumanan & Nagaraj, 2013). The result showed FA based PID performed more efficiency than the conventional PID controller. In addition, there were some researches which compared a good controlled performance of FA method with PSO and GA (Bendjeghaba, 2013, 2014; Madasamy & Ravichandran, 2015). The results concluded that FA method could perform better than PSO and GA methods based on PID controller especially less overshoot and settling time. Beyond PID and PI controllers, an integral-proportional derivative (I-PD) control was one of the new modified PID controllers that are popular to implement. For example, there was the usage of I-PD controller to control a resonance ratio control system and feedback signal of reaction force which was response for Industrial robot (Yabuki, Ohishi, Miyazaki, & Yokokura, 2016). Firefly algorithm that modified with particle swarm optimization (Meena & Chitra, 2018) employed to tune PID and I-PD controllers for the reduction of the peak overshoot and the integral time absolute error (ITAE). The result illustrated that this algorithm could handle the peak overshoot and ITAE and the firefly algorithm could speed to find the optimized values. The particle swarm optimization (PSO) tuning I-PD (Prasad & P A, 2012; Prasad, Meenakumari, & Balakrishnan, 2014) used to optimal control parameters of proportional, integral time derivative time gains. PSO is the heuristic evolution optimization algorithm that inspired from nature. The proportional, integral time derivative time gains were indicated as particles in a three dimensional problem space. Through the completion of a number of iterations the particle would seek to find an optimum place. The final result was the optimum value of controller parameters shown in less integral square error (ISE), integral error (IAE), and settling time. Besides, I-PD controller cooperated with genetic algorithm (GA) to control twin rotor MIMO system. The result showed better performance comparing with PID controller with genetic algorithm (GA) (Saha & Chakraborty, 2016), whereas fuzzy logic tuned I-PD controller performance that delivered a reduction of the overshoot and settling time compared with Ziegler-Nichols tuned PID controller, fuzzy logic controller (Anbarasan, Prasad, Meenakumari, & Balakrishnan, 2013). The methodology of fuzzy logic controller consists of three processes named fuzzification, inference, and defuzzification. For applying fuzzy logic to tune I-PD controller, there were two input and three output variables. The error and the changed rate of errors are input variables and gains of proportional, integral time derivative time and controllers are output variables.

All previous literature reviews as previous mention is purposed deeply to provide good performance for the machine controller. For this research, the plastic molding process control is used to be the challenging task to control barrel temperature. According to research's Ke Yao *et al.* (Yao & Gao, 2007; Yao, Gao, & Allgöwer, 2008; Liu, Yao, & Gao, 2009) that studied about barrel temperature control and sought the desirable barrel temperature to provide a minimal start-up time and reducing overshoot of temperature control. Results affected to productivity, product quality and the temperature response models of three front end zones in the barrel cylinder, which were selected. Ke Yao's temperature response models were employed to this research experiment (Liu *et al.*, 2009). The research aim is used of firefly algorithm tuned I-PD controller and compared with other controller based on Ke Yao's temperature response models (Liu *et al.*, 2009).

2. Materials and Methods

2.1 Heating system for plastic injection molding and modified PID controller

2.1.1 Barrel temperature control system for plastic injection process

In daily life, plastic products have been become a part of daily activities such as bottle caps, toys, laptop housing, food boxes, and others. Most of the plastic products were produced from Injection molding machine. The first process is the plastic pellets fed into the barrel cylinder. The barrel is then heated with heater bands in each zone for melting plastic materials. Next, reciprocating screw shows inside the barrel cylinder rotates to push the plastic melt towards the mold end. During plastic injection process, the temperature inside the barrel needs to maintain at the set point (Dubay, Diduch, & Li, 2004). For this research, PID and I-PD controller are implemented in heat-up process in order to state the operating temperature at 200 °C according to research's Ke Yao et al (Liu *et al.*, 2009).

2.1.2 PID Controller

For PID controller, PID controls a system to get steady state of signal and tries to maintain temperature process of barrel. The PID diagram of conventional PID controller illustrates in Figure 1. The output perform of PID controller is given as Equation 1:

$$u(t) = K_p e(t) + \frac{1}{T_i}\int e(t)dt + T_d\frac{de(t)}{dt} \qquad (1)$$

where K_p is proportional gain, T_i is integral time, and T_d is derivative time. The conventional PID controller can decrease the overshoot response time and also enforce to less derivation of signal (Jeong *et al.*, 2015). The *r(t)* is the measurement of points. The error *e(t)* is the value of set point difference and real signal. The *u(t)* is the output of the controller that used to put to the process.

2.1.3 I-PD Controller

In I-PD controller, integral plus proportional and derivative (I-PD) act on the error (steady state error) and maintain the process variable settling (temperature). I-PD diagram of the I-PD controller is shown in Figure 2. The outcome equation of I-PD controller is given as the Equation 2:

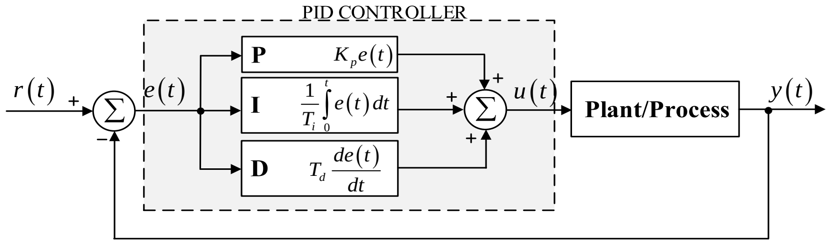

Figure 1. PID controller

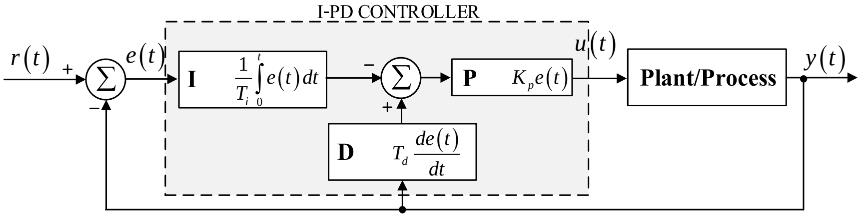

Figure 2. I-PD controller

$$u(t) = K_p\left[\frac{1}{T_i}\int e(t)dt - y(t) + T_d\frac{de(t)}{dt}\right] \tag{2}$$

where K_p is proportional gain, T_i is integral time, and T_d is derivative time. The error E(s) is the difference between the set point, R(s) is the measured process variable. U(S) is the input to the process and Y(s) is the output of the controller.

2.2 The temperature response model and its Ziegler-Nichols Tuning

2.2.1 Process model

The heat barrel of plastic injection molding machine normally consists of three zone or more. This research uses the temperature response models of (Liu *et al.*, 2009) that are shown in the Equation 3 to 5.

$$Zone\ 1 = \frac{62.612e^{-29.4s}}{(153.037s+1)^2} \tag{3}$$

$$Zone\ 2 = \frac{62.7337e^{-27.8s}}{(145.299s+1)^2} \tag{4}$$

$$Zone\ 3 = \frac{31.4213e^{-23.4s}}{(113.3369s+1)^2} \tag{5}$$

2.2.2 Ziegler-Nichol (ZN) Tuning

The wide Ziegler-Nichols tuning method usually use to control PID controller with the critical gain (K) and ultimate period (P_u) then three output controllers can be derived following Equation 6 to 8.

$$K_p = 0.6K \tag{6}$$

$$T_i = 0.5Pu \tag{7}$$

$$T_d = 0.125Pu \tag{8}$$

Then implementing Ziegler-Nichols (ZN) Tuning into the temperature response models is shown in Table 1.

2.3 Firefly algorithm methodology and the structure of tuning PID and I-PD controller

2.3.1 Firefly algorithm established for optimized parameters of controller

Firefly algorithm optimization is implemented to tune PID and I-PD controllers for getting less overshoot and creating the shortest settling time of temperature control. This algorithm generated by Yang (Yang, 2009) that emulated from flashing pattern of firefly behavior. This algorithm have to create the initial firefly population (n) that likely represented in some random searches of solution set which results the same as the error signal. Controlled parameters is represented the attractiveness. This method must consist of the light absorption coefficient, and randomization parameters. For firefly behavior, one firefly will move forward to contact the other fireflies by seeking a firefly contained a high of light intensity that can evaluate the distance of firefly i to another attractive firefly j in Equation 9:

$$X_i = X_i + \beta(X_j - X_i) + \alpha(rand - 0.5) \tag{9}$$

where β and α are parameters of attractiveness and randomization, then r_{ij} is Cartesian distance (distance between two fireflies). The attractiveness factor can be generated from the Equation 10.

$$\beta = \beta_0 e^{-\gamma r_{ij}^2} \tag{10}$$

Table 1. Tuning parameters using Ziegler Nichols method

Zone	Method	K_p	T_i)sec(	T_d)sec(
Zone1	ZN	0.1062	151.3890	37.8472
Zone2	ZN	0.1064	143.4331	35.8583
Zone3	ZN	0.1979	116.3657	29.0914

Given β_0 is the attractiveness at Cartesian distance $(r_0) = 0$ and γ is a light absorption coefficient. The firefly algorithm methodology can illustrate as shown in Figure 3.

2.3.2 Optimal temperature responding process model

Before going to optimal parameters of PID and I-PD controller to get a stable temperature control system, the integral of absolute error (IAE) is employed to be the objective model as indicated in Equation 11 and 12, respectively.

Find $X = |K_p, T_i, T_d|$ (11)

Minimize $f(x) = I$ (12)

I = The Integral of Absolute Error

$$I = \int |e(t)|\, dt$$

Subject to: $0 \le K_p \le 1000$, $0 \le T_i \le 1000$, $0 \le T_d \le 1000$

2.3.3 Firefly algorithm tuned PID and I-PD controller

After establishing optimal model, firefly algorithm gets into the system for seeking optimal tunes of PID and I-PD controller. This concept step is the reduction of unstable signal and retention of temperature set point during operation by setting-up firefly parameters as the number of iterations equal to 200, the size of population equal to 50, the absorption coefficient equal to 0.5, the maximum attractiveness equal to 0.5, and the random perturbation rate equal to 0.2 according to researches of Sudsawat & Sriseubsai, (2017) and running on Intel® Core i3-2310M CPU @ 2.10GHz personal computer with 4 GB RAM memory. The temperature control system with firefly algorithm of PID and I-PD controllers are shown in Figure 4 and 5.

Then placed all the concepts for simulated tests, the Figure 6 is shown the Simulink tests, which was compared not only between Ziegler-Nichols (ZN) tuning PID and I-PD, but also firefly algorithm tuning PID and I-PD. Then implementing Firefly algorithm tuning into the temperature response models is shown in Table 2.

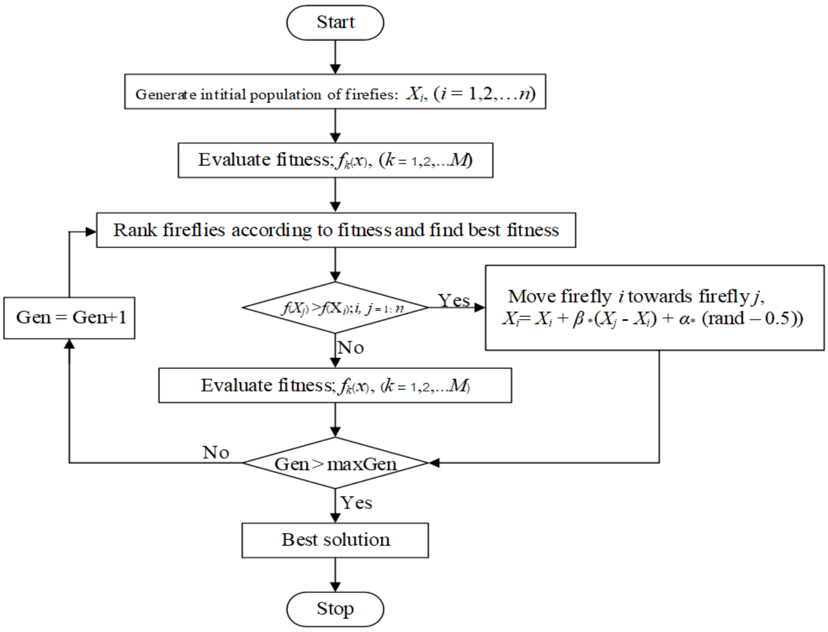

Figure 3. Flow chart of firefly algorithm

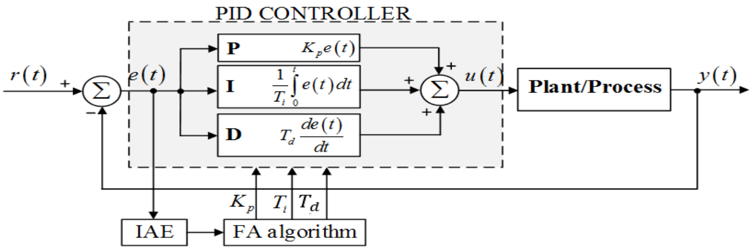

Figure 4. Temperature control system with firefly algorithm of PID controller

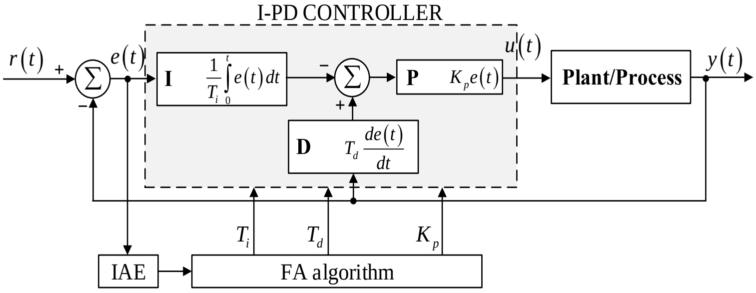

Figure 5. The temperature control system with Firefly algorithm of I-PD controller

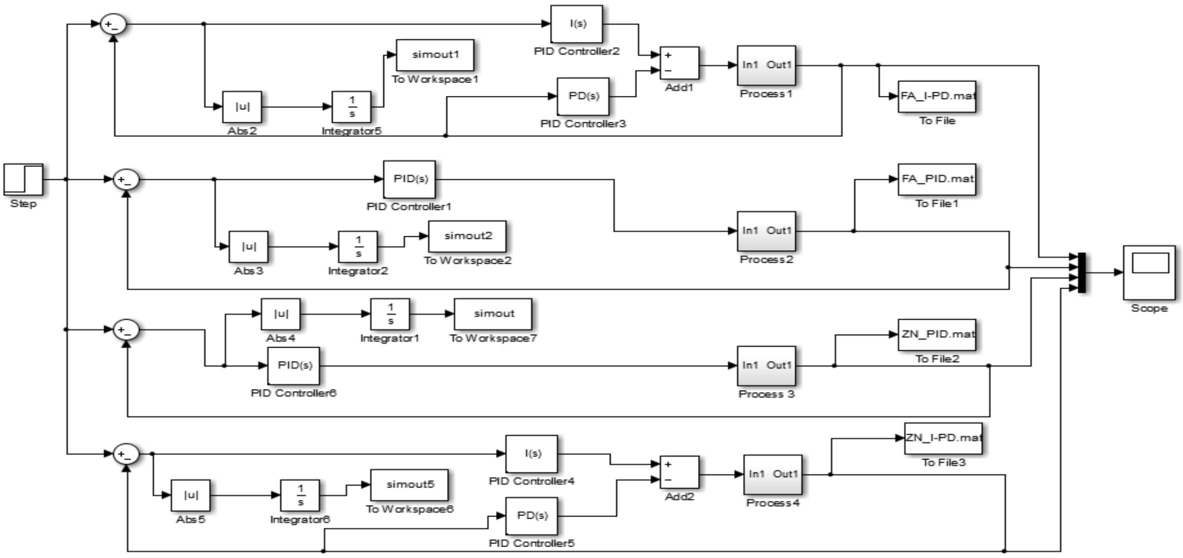

Figure 6. Simulink block diagram for barrel heating system compared between Ziegler-Nichols (ZN) tuning PID and I-PD, firefly algorithm tuning PID and I-PD

Table 2. Controller parameters for PID and I-PD Controllers using FA method

Zone	Controller	K_p	T_i)sec(	T_d)sec(
Zone1	PID	0.0817	317.0272	78.7318
	I-PD	0.2202	126.8109	41.2707
Zone2	PID	0.1631	226.4480	38.0960
	I-PD	0.2039	144.9267	44.4454
Zone3	PID	0.1387	226.4480	35.5563
	I-PD	0.4727	113.2240	33.6515

2.3.4 Implemented firefly algorithm to tune PID and I-PD controller for controlling heaters

After proved the tuning results through Simulink, this step tried to employ firefly algorithm in STM32F4DISCOVERY board controller that works with Matlab program to cope with temperatures of injection heaters for three zones. The injection heater barrel of the Toshiba 80 TONs was employed for the experiment as shown in Figure 7.

3. Results and Discussion

All of optimal parameters from Ziegler-Nichols (ZN) tuning, and firefly algorithm tuning were used to provide a comparison of performances. Three results present namely peak of overshoot, settling time, and rising time. Figure 8 to 10 represent the simulation outputs by Ziegler-Nichols (ZN) tuning PID, I-PD, and firefly algorithm tuning PID, I-PD, respectively.

From the Table 3, it can be concluded that I-PD controller through FA method provides a good performance as less overshoots and settling time than ZN, PSO ,and fuzzy logic control methods. Meanwhile, if we investigate only I-PD controller, it can summarize that tuning I-PD via FA method gains less overshoot than Suji's PSO tuning I-PD (Prasad & P A, 2012), and Anbarasan's Fuzzy tuning I-PD (Anbarasan, Prasad, Meenakumari, & Balakrishnan, 2013) at 2.25% and 1.5%, respectively, for Barrel temperature (zone 1), 3% and 1.75 %, respectively, for Zone 2, and 0.82% and 0.57%, respectively, for Zone 3. Referring to the Settling time, each zone of FA method tends to reduce by comparing with PSO, Fuzzy methods, and Kanagalakshmi's Internal Model Controller (IMC) (2014), except the settling time of zone 1 that took more time comparing with PSO method at 11.86% but gained less efficient percent overshoot.

Moreover, this research implemented firefly algorithm via board controller to test heat barrels for two barrels of Toshiba 80 Tons' injection molding machine by setting points of heater at 190 °C and 180 °C for zone1, and

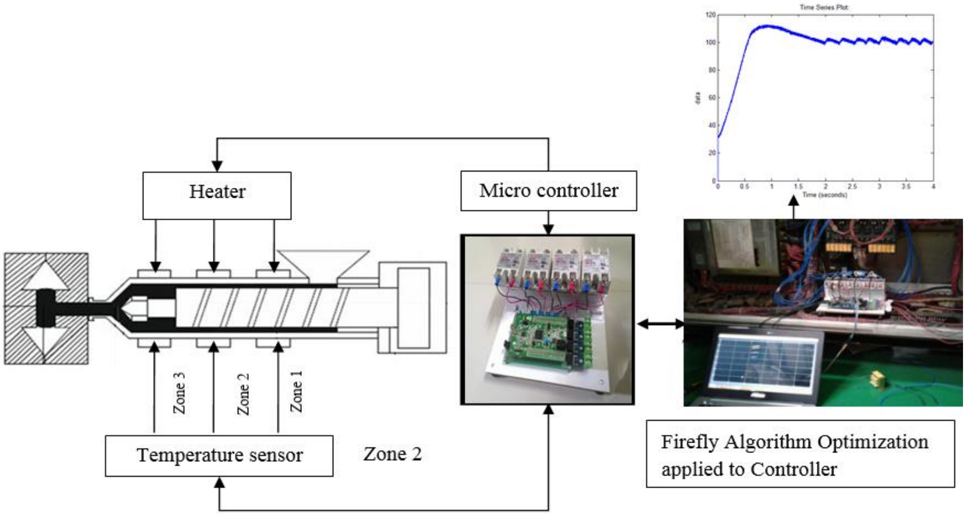

Figure 7. Implementation of injection heater barrel controlled by STM32F4DISCOVERY for imperial experiments

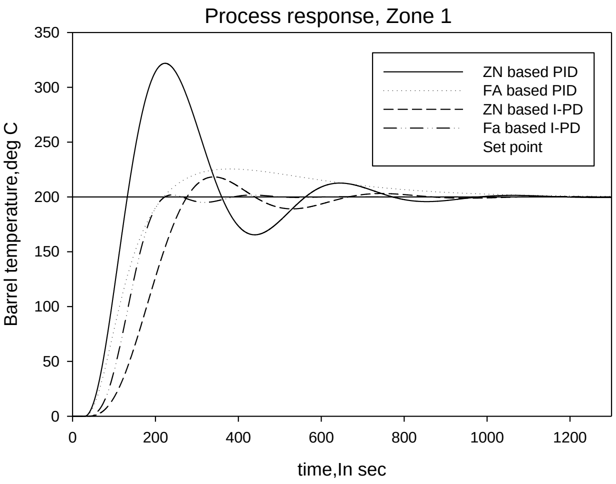

Figure 8. Response of barrel temperature control in zone 1

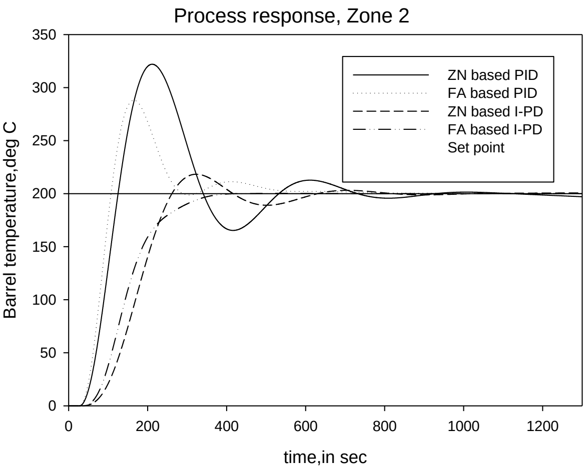

Figure 9. Response of barrel temperature control in zone 2

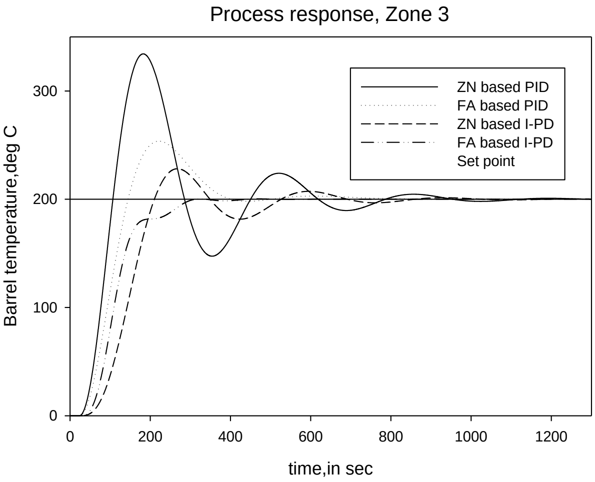

Figure 10. Response of barrel temperature control in zone 3

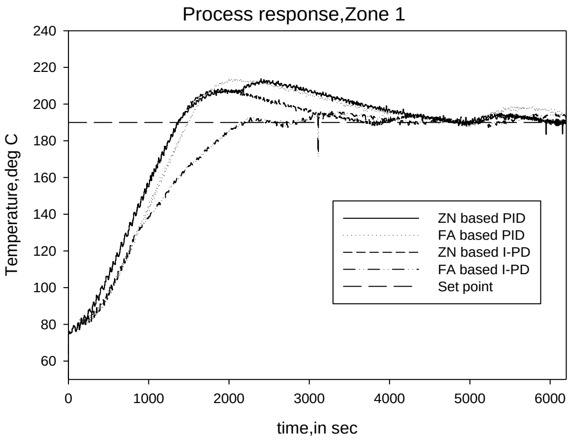

Figure 11. Response of barrel temperature control in zone 1 of imperial test

zone 2, respectively. Figure 11 presents FA based on I-PD controller that can provide setting time earlier than other controller and less overshot by using the set point temperature at 190 ^{o}C that is most similar trend as Simulink's results in Table 3. Whereas, the empirical test of zone 2 that is transition zone of injection molding process seem like the variant results as shown in Figure 12 because the transition zone had variant temperature during the polymer is transforming from solid to liquid that means difficult temperature control in this zone. Results indicate that FA based on I-PD still can handle temperature control comparing the other for set point temperature at 180 ^{o}C. For zone 3, the result provide FA based on I-PD that can achieve quickly a set point at 170 ^{o}C than other controllers and also use setting time less than other around 2,000 sec as shown in Figure 13.

4. Conclusions

This research introduces a novel approach based on firefly algorithm (FA) for tuning I-PD controller in the temperature response models. For the empirical results of FA method tuning I-PD can reduce settling time and peak overshoot more effective than uses PSO, fuzzy tuning PID and I-PD controllers. Therefore, it can be concluded that FA method can generate a good performance for temperature control for injection molding barrel.

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Table 3. Controller parameters for PID and I-PD Controllers using FA method

Zone	Performance Specification	PID using ZN	PID using FA	I-PD using ZN	I-PD using PSO (Prasad & P A, 2012)	Fuzzy I-PD (Anbarasan *et al*, 2013)	IMC control (Kanagalakshmi *et al*, 2014)	I-PD using FA
Zone 1	Settling time (min)	19.22	18.33	17.21	7.25	13.97	18.67	8.11
	Peak Overshoot (%)	61.00	13.00	9.00	3.25	2.50	0.00	1.00
Zone 2	Settling time (min)	18.20	14.65	16.31	7.37	12.08	17.25	6.55
	Peak Overshoot (%)	60.99	44.1	9.00	3.00	1.75	0.00	0.00
Zone 3	Settling time (min)	18.38	13.63	16.68	5.3	13.07	21.08	5.21
	Peak Overshoot (%)	67.13	27	14	1	0.75	0.00	0.18

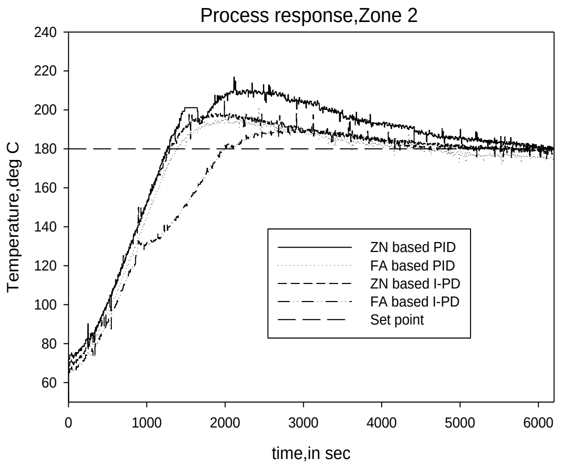

Figure 12. Response of barrel temperature control in zone 2 of imperial test

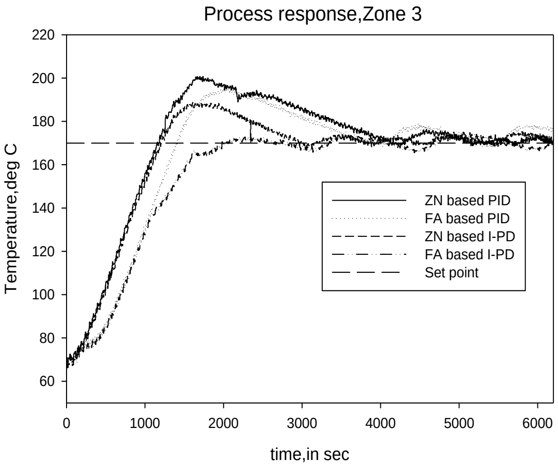

Figure 13. Response of barrel temperature control in zone 3 of imperial test

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