wjert, 2024, Vol. 10, Issue 5, 147-164. *Review Article* ISSN 2454-695X

World Journal of Engineering Research and Technology

WJERT

www.wjert.org SJIF Impact Factor: 7.029

THERMOPLASTICS INJECTION MOLDING MACHINE CONTROL, PART I: MOLD TEMPERATURE CONTROL USING I-PD COMPENSATOR, PD-PI AND 2DOF-2 CONTROLLERS COMPARED WITH A PID CONTROLLER

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Article Received on 11/03/2024 **Article Revised on 01/04/2024** **Article Accepted on 21/04/2024**

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ABSTRACT

The control of mold temperature in injection molding machines is essential to maintain production of molded plastic parts with good quality and minimum defects. The paper presents the control of mold temperature using a compensator from the second generation of control compensators (I-PD) and two controllers from the second generation of PID controllers (PD-PI and 2DOF-2). A proper tuning technique is selected to tune the compensator/controllers using an ITAE performance index. The step time response of the control system using the three proposed compensator/controllers is presented and compared with using a PID controller to control the same mold temperature and the time-based characteristics are compared. The comparison reveals the best compensator/controller among the four compensator/controllers depending on a graphical and quantitative comparison study.

KEYWORDS: Injection mold temperature control, I-PD compensator, PD-PI controller, 2DOF-2 controller, PID controller, compensator/controllers tuning.

INTRODUCTION

Rolling mills are one of the strategic processes used for metal strips and shapes production required for too many metallic industries and construction purposes. Rolling mills have key processing variables such as rolling force, strip thickness and strip roughness. This paper proposes control compensators from the second generation for the control of rolled strip thickness. We start by taking an idea about some of the research work regarding strip thickness modeling and control.

Brown, Maliotis and Gibby (1999) described the application of self-tuning PID controller to a single strand cold rolling aluminum mill. Their design was based on an adaptive control scheme where the gain parameters were adjusted according to estimates of the process parameters. They discussed also process parameters estimator algorithm.[1] Hu and Ehmann (2000) proposed an enhanced analytical rolling process model capable of handling dynamic variations exerted by roll vibrations. They established a linearized form of the model and presented experiments verifying its accuracy.[2] Zarate (2005) presented a method for strip thickness adjustment in a single strand rolling mill using three control parameters: roll gap, front tension and back tension using a predictive model based on the process sensitivity equation. The proposed control system calculated the necessary adjustment based on a a predictive model for the output thickness. He used a first-order dynamic model for the strip thickness with an integrator and used a PD-PI controller to perform the control action.[3] Gazina, Yong and Xinming (2008) developed a fuzzy-neural network control applied to the screw-down mechanism of a cold rolling mill. The application of the fuzzy-neural network control wqs superior in the static and dynamic control performance (as their claim).[4]

Cavazzana and Dentifilho (2014) proposed a gain scheduling control for industrial rolling mills. They proposed two controllers acting on gap sub-system to compensate process disturbances. They used the optimal quadratic regulator method to tune the controllers. They claimed that their technique led to less output thickness variations compared with other proposals.[5] Kucsera and Beres (2015) analyzed the automatic gauge control system of a hot rolling mill and described different methods to improve its performance. They compensated the process disturbances and developed an adaptive PI controller to achieve fine thickness control. The model used in their control scheme was a first-order with time delay. They discussed also the use of a predictive controller using Smith Predictor.[6] Ahang, Zhang and Chen (2016) discussed the design and implementation of a steel plate mill and the design of precession models and control actuators. They discussed also control loop strategies and presented the performance results achieved during the startup of a steel plate mill.[7]

Saxena and Sharma (2017) used the automatic gauge control system to realize high accuracy in the strip exit thickness in a rolling mill. They designed a PI controller in the outer-loop for strip thickness control and a PD controller in an inner-loop the actuator position. For eccentricity compensation, they used a fuzzy-neural network with online tuning. They used a first-order model with an integrator for the actuator position control.[8] Macedo et al. (2019) claimed that 60 ^{o}C mold temperature is used to decrease cycle molding time and process final cost and a dynamic mold heating and cooling control technology called rapid heating and cooling molding was employed. They manufactured an experimental injection mold to produce standard tensile and flexure specimens.[9] Giang et al. (2021) outlined that a high mold temperature with preheating of the mold cavity surface was required to improve the melt flow length. They applied and verified using a flow focusing device (FFD) to improve the heating efficiency. They applied preheating of the mold using external gas-assisted mold temperature control. They carried out simulations and experiments within air temperature of 400 ^{o}C and 20 s heating time with the application of various FFD types where the heating efficiency was improved and the melt flow length was improved.[10]

Uyen, Do and Minh (2022) used a pre-heating step with the internal gas heating method to heat the cavity surface before the filling step to reduce the frozen layer and improve the filling ability of the composite molded material in a micro-injection molding process. They used an internal gas-assisted mold temperature control system with pulsed-cooling system. They analyzed the temperature distribution and heating rate through observing the heating process using an infrared camera. They claimed that the filling capacity of the composite material increased to 100 % with local heating at the melt output area where the gas temperature increased to 400 ^{o}C with 20 s heating cycle. No dynamic temperature control was shown.[11] Guo, Yangm Fu and Zhao (2023) claimed that the production of polyether ether ketone (PEEK) injection molded products require high mold temperature so that they can be manufactured. They designed a mold temperature rising system based on induction heating with high heating rate. They showed through finite elements analysis and experimentation that the heating method increased the efficiency by 5600 % when the mold temperature increased from 150 to 180 ^{o}C compared to electric heating. The surface quality was about 10-61 % higher than oil heating and the mechanical properties were improved by more than 18 %.[12] Hopmann, Kahve, Fritsche and Felleyhoff (2024) claimed that to reduce molded part warpage, homogenization of melt properties in the mold is necessary. They designed a mold with 18 heating ceramics using a newly developed control loop adjusting target values for the upcoming molding cycle based on error in the previous cycles aiming at homogenizing the local mold temperatures over multiple cycles. They claimed that the plate-shaped warpage was reduced by 10 % with their temperature homogenization approach.[13]

Controlled mold temperature

The injection molding machine used by F. Gao for the investigation of mold temperature control was '*Danson Metalmec 2 1/3 oz reciprocating screw model 60-SR*' [1]. The mold under control was equipped with cavity surface temperature sensor, mold metal temperature sensor, heat flux sensor and cooling medium flow rate sensor.[1] Gao concluded that the best control variable for the mold surface temperature is the coolant temperature where he outlined the mold temperature dynamic model for this variable and for another two possible control variables. Here, I consider his conclusion and use his transfer function of the model temperature process which was a first-order model with time delay given in Eq.1.[1]

$$G_p(s) = 0.756 \exp(-2s) / (6.925+1) \qquad (1)$$

The exponential form is approximated by a second-order Pade approximation.[14]

The process transfer function (Eq.1) with the second-order Pade approximation becomes:

$$G_p(s) = (3.024\, s^2 - 9.072\, s + 9.072) / (27.7s^3 + 87.1s^2 + 95.1s + 12) \qquad (2)$$

The unit step time response of mold temperature having the dynamics defined by Eq.2 is shown in Fig.1 as generated by the '*step*' command of MATLAB.[15]

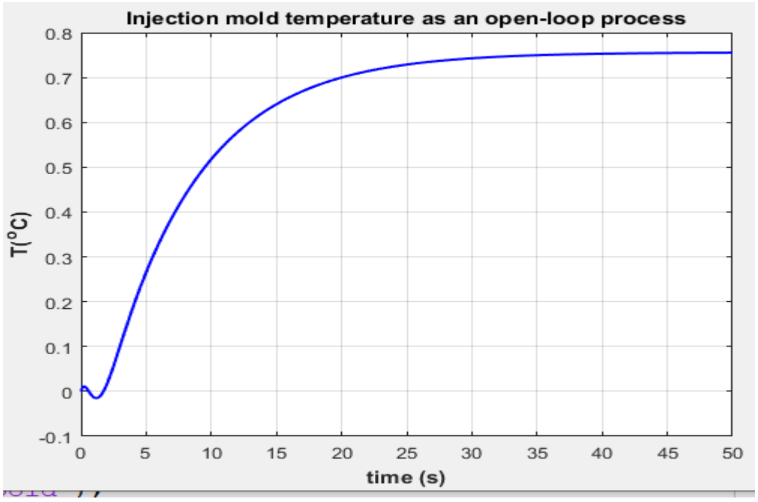

Figure 1: Step time response of the mold temperature.

Comments

- The mold-cavity surface temperature process is stable.
- It has a steady-state error of 0.244 ^oC.
- It has zero maximum percentage overshoot.
- It has a settling time of 4.64 s.
- It has a maximum undershoot of –0.015 ^oC

Controlling the Mold Temperature Using an I-PD compensator

The I-PD compensator was introduced by the author to control second-order-like processes,[16] greenhouse temperature,[17] boiler steam pressure,[18] rocket pitch angle[19] and rolling strip thickness control.[20] It has the structure shown in Fig.2.[16] It has an integral control mode in the forward path just before the process to be controlled and a PD- control mode in the feedback path of the closed-loop control system.

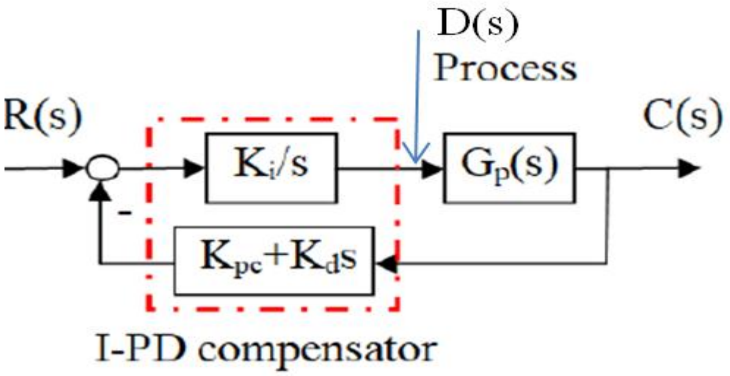

Figure 2: Structure of the I-PD compensator.[16]

The I-PD compensator has the transfer functions $G_I(s)$ and $G_{PD}(s)$ given by

$G_I(s) = K_i/s$

and $G_{PD}(s) = K_{pc}+ K_ds$ (3)

Where

K_i = integral gain of the integral control mode

K_{pc} = proportional gain of the PD control mode

K_d = derivative gain of the PD control mode

It has three gain parameters to be tuned for stable control system and for good performance in terms of the control system steady-state error, maximum overshoot and settling time.

The I-PD compensator is tuned using the optimization toolbox of MATLAB[21] minimizing the ITAE performance index.[22]

- Through the investigation of the closed-loop transfer function for reference input tracking it was found that the step time response will have a zero steady-state error if the proportional gain K_{pc} of the I-PD compensator is set to a unit value. That is:

$K_{pc} = 1$ (4)

- The other parameters of the I-PD compensator are tuned using the MATLAB optimization toolbox[21] and an ITAE performance index.[22] The tuned integral and derivative gain parameters of the I-PD compensator are:

$K_i = 0.599782$, $K_d = 4.769339$ (5)

- The unit step time response of the closed-loop control system the reference input is evaluated using the transfer function and the step command of MATLAB.[15]
- The unit step time response of the control system for the rolling strip thickness with reference and disturbance inputs using Eqs.2, 3, 4 and 5 and transfer functions derived from the block diagram in Fig.2 is shown in Fig.3.
- A second-order high pass filter is used with the disturbance input to improve the characteristics of the control system regarding the disturbance rejection.

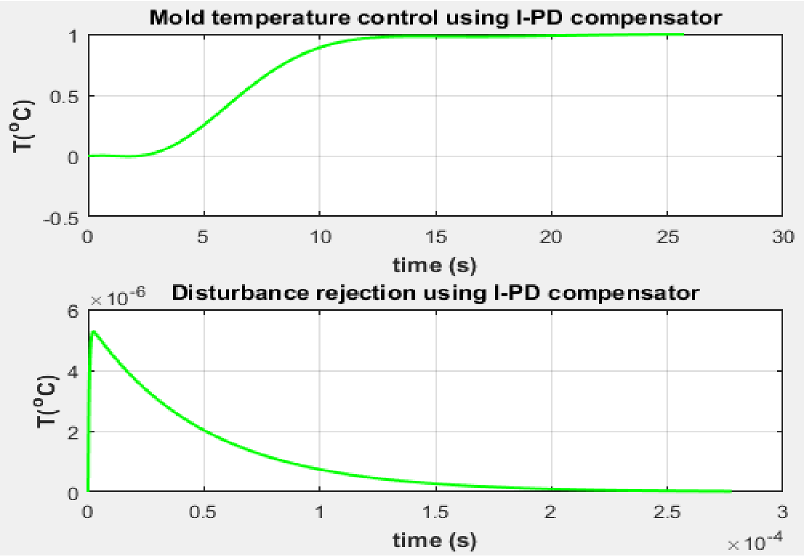

Figure 3: Mold temperature controlled by an I-PD compensator.

Comments

- The I-PD compensator provided a reference input tracking step time response having the following characteristics:
- Maximum percentage overshoot: Zero

- Maximum undershoot: -0.004 ^oC
- Settling time: 13 s
- The success of the I-PD compensator to reject the disturbance input is measured by the following characteristics:
- Maximum mold temperature step time response: 5.26×10^{-6} ^oC
- Minimum mold temperature step time response: zero
- Settling time to zero (Approximate): 0.00025 s

Controlling the Mold Temperature Using a PD-PI Controller

The PD-PI controller was introduced by the author to control a number of difficult processes since 2014 including: its use in controlling first-order delayed processes,[23] highly oscillating second-order process,[24] integrating plus time-delay process,[25] delayed double integrating process,[26] third-order process,[27] boost-glide rocket engine,[28] rocket pitch angle,[29] LNG tank pressure,[30] boiler temperature [31] boiler-drum water level,[32] greenhouse internal humidity,[33] coupled dual liquid tanks,[34] BLDC motor,[35] furnace temperature,[36] electro-hydraulic drive[37] and rolling strip thickness,[38] The PD-PI controller is composed of two elements: PD-control mode, $G_{c1}(s)$ in cascade with a second PI-control mode, $G_{c2}(s)$ just after the error detector.

The two elements have transfer functions given by

$G_{c1}(s) = K_{pc1} + K_d s$

and $G_{c2}(s) = K_{pc2} + K_i/s$ (6)

Where

K_{pc1} = proportional gain of the PD-control mode.

K_d = derivative gain of the PD-control mode.

K_{pc2} = proportional gain of the PI-control mode.

K_i = integral gain of the PI-control mode.

- The PD-PI controller has four gain parameters (K_{pc1}, K_d, K_{pc2} and K_i) to be tuned to satisfy the objectives of using the controller to control the mold temperature and provide good control system performance for reference and disturbance inputs.
- To control the rolling strip thickness for reference input tracking, the transfer function of the closed loop control system is derived using the block diagram and Eqs.2 and 6.
- The PD-PI controller is tuned using the same tuning procedure used with the I-PD compensator.

- The tuned parameters of the PD-PI controller using an ITAE performance index [22] are as follows:

K_{pc1} = 0.2662409 , K_d = 1.839538

K_{pc2} = 0.296225 , K_i = 1.157272 (7)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs using the controller parameters in Eq.7, the unit step time response is shown in Fig.4.

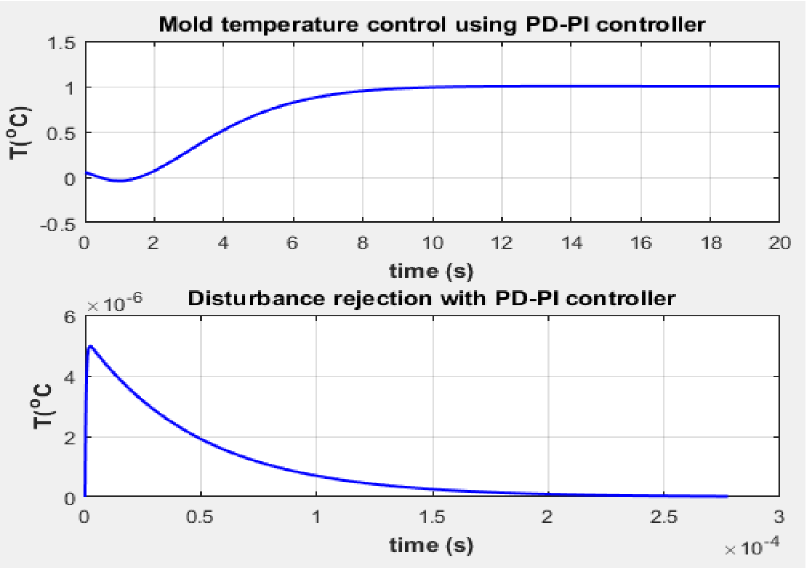

Figure 4: Mold temperature controlled by a PD-PI controller.

Comments

- ➢ The PD-PI controller provided a reference input tracking step time response having the following characteristics:
- Maximum percentage overshoot: 0.14 %
- Maximum undershoot: -0.038 °C
- Settling time: 9.20 s
- ➢ The success of the PD-PI controller to reject the disturbance input is measured by the following characteristics:
- Maximum mold temperature step time response: 4.96 x 10^{-6} °C
- Minimum mold temperature step time response: zero
- Settling time to zero (Approximate): 0.00025 s

Controlling the Mold Temperature Using a 2DOF-2 Controller

The 2DOF-2 controller was introduced by the author to control a number of difficult processes since 2014 including: The author used different structures of 2DOF control to control a variety of industrial processes with bad dynamics such as: liquefied natural gas pressure control,[30] coupled dual liquid tanks,[34] boost-glide rocket engine,[28] BLDC motor control,[35] highly oscillating second-order process,[24] delayed double integrating processes,[26] boiler drum water level,[32] boiler temperature,[31] electro-hydraulic drive,[37] rolling strip thickness[38] and furnace temperature.[39]

The structure of the 2DOF controller used in the present work is shown in Fig.5.[40] The 2DOF-2 controller is composed of two control elements: reference input element receiving its input from the reference input of the control system which is a PI-control mode having $G_{ff}(s)$ transfer function and a feedback element receiving its input from the mold temperature signal which is a PID-control mode having $G_c(s)$ transfer function.

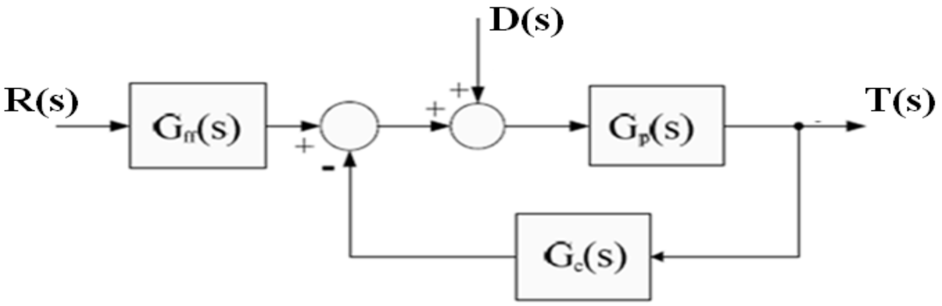

Figure 5: Mold temperature control using a 2DOF-2 controller.[40]

The transfer functions of the 2DOF-2 controller are as follows

$G_{ff}(s) = K_{pc1} + (K_i/s)$

and $G_c(s) = K_{pc2} + (K_i/s) + K_d s$ (8)

Where

K_{pc1} = Proportional gain of the PI-control mode.

K_i = Integral gain of the PI and PID-control modes.

K_{pc2} = Proportional gain of the PID-control mode.

K_d = Derivative gain of the PID-control mode.

The 2DOF-2 controller has four gain parameters to be tuned to provide the required performance of the closed-loop system of the mold temperature control. The controller is tuned following the same procedure used with the I-PD compensator and the PD-PI controller. The tuned parameters of the 2DOF-2 controller are as follows:

K_{pc1} = 3.067956, K_i = 0.283122

K_{pc2} = 2.846814, K_d = 1.306859 (9)

The closed loop transfer functions of the control system for both reference and disturbance inputs are derived from the block diagram in Fig.5 using the process transfer function in Eq.2 and the controller transfer functions in Eq.8 with the tuned controller parameters in Eq.9. The unit step time response of the control system is plotted using the step command of MATLAB and shown in Fig.6 for both inputs.

Comments

- The 2DOF-2 controller provided a reference input tracking step time response having the following characteristics:
- Maximum percentage overshoot: 0.497 %
- Maximum undershoot: -0.0468 °C
- Settling time: 6.69 s
- The success of the 2DOF-2 controller to reject the disturbance input is measured by the following characteristics:
- Maximum mold temperature step time response: 4.60 x 10^{-6} °C
- Minimum mold temperature step time response: zero
- Settling time to zero (Approximate): 0.00025 s

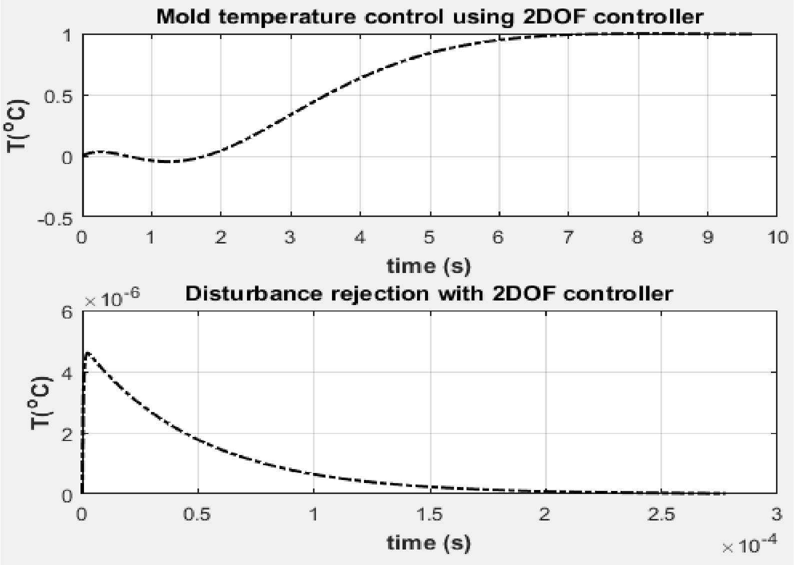

Figure 6: Mold temperature controlled by a 2DOF controller.

Characteristics Comparison of the Three Compensator/controllers with a PID controller

- The reference for the comparison of the performance of the proposed compensator/controllers is a tuned PID controller used in a previous work to control the same process by Gao.[1]
- The PID controller was tuned by Gao as a digital controller having the tuned gain parameters:

$K_{pc} = 2.4482; T_i = 7.1345; T_d = 0.68809$ (10)

Where

T_i = integral time constant of the PID controller.

T_d = derivative time constant of the PID controller.

- I tried using the digital PID controller parameters in Eq.10 as the gain parameters of an analog PID controller to control the same process (mold temperature) and plotted the step response of the control system for a unit step input not for 4 ^oC as Gao did. The result was amazing. The analog PID controller gave better performance than the digital one of Gao[1] as depicted in Fig.7.

Comments

➢ The PID controller provided a reference input tracking step time response having the following characteristics:

- Maximum percentage overshoot: 0.84 % (Compared with 3.86 % for the digital PID controller of Gao.[1])
- Maximum undershoot: -0.0767 ^oC
- Settling time: 10.10 s (compared with 18.2 molding cycles according to the presentation of Gao.[1]).

➢ The success of the PID controller to reject the disturbance input is measured by the following characteristics:

- Maximum mold temperature step time response: 4.44×10^{-6} ^oC
- Minimum mold temperature step time response: zero
- Settling time to zero (Approximate): 0.00025 s

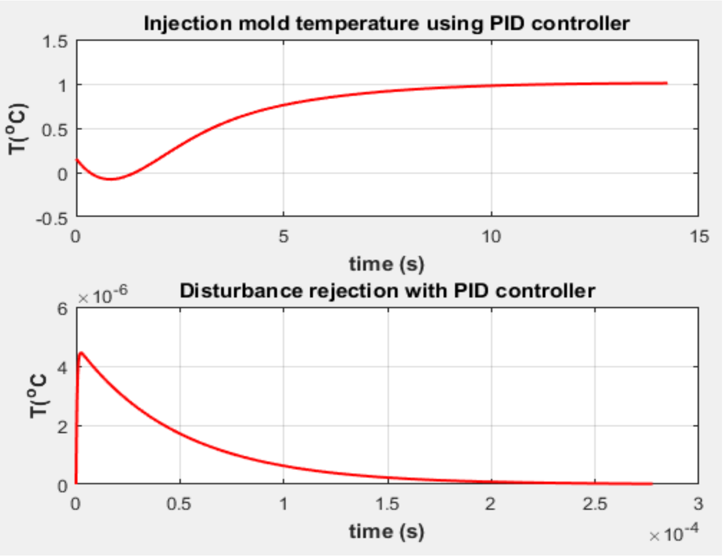

Figure 7: Mold temperature controlled by a PID controller.

- The characteristics comparison takes two forms: graphical and quantitative ones as follows.
- *Graphical comparison*:

➢ For the reference input: The comparison is shown in Fig.8 for PID controller, I-PD compensator, PD-PI controller and 2DOF controller.

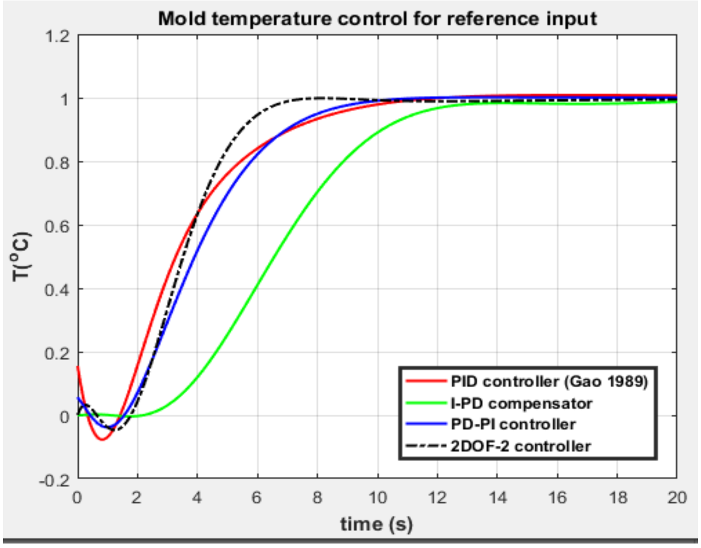

Figure 8: Comparison of reference input step time responses for the mold temperature process.

➢ For the disturbance input: The comparison is presented in Fig.9 using the tuning parameters of the PID controller presented by Gao.[1]

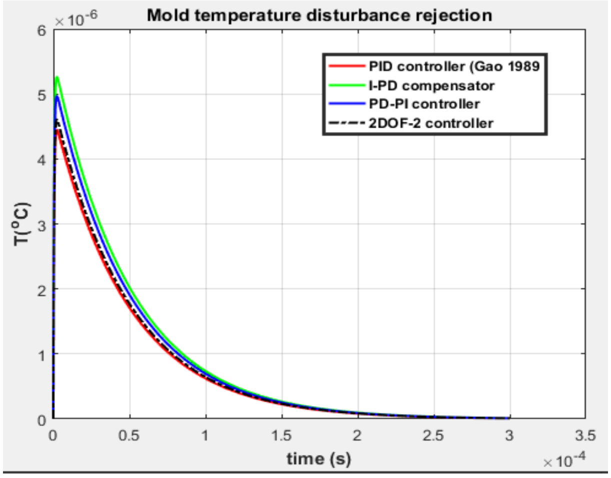

Figure 9: Comparison of disturbance input step time responses for mold temperature control.

- *Quantitative comparison*: The time-based characteristics of the control system for the rolling strip thickness control are quantitatively compared in Table 1 for reference input tracking and Table 2 for disturbance input.

Table 1: **Reference input time-based characteristics of the mold temperature control using PID controller, I-PD compensator and PD-PI, 2DOF-2 controllers.**

Characteristics	PID controller (Gao tuning)	I-PD compensator	PD-PI controller	2DOF-2 controller
Maximum overshoot (%)	0.83	0	0.14	0.497
Maximum undershoot (°C)	-0.0767	-0.004	-0.038	-0.0467
Settling time (s)	10.1	13.0	9.2	6.69

Table 2: **Disturbance input time-based characteristics of the mold temperature control using PID controller, I-PD compensator and PD-PI, 2DOF-2 controllers.**

Characteristics	**PID controller (Gao Tuning)**	**I-PD compensator**	**PD-PI controller**	**2DOF-2 controller**
Maximum time response (°C)	4.44 x 10^{-6}	5.26 x 10^{-6}	4.96 x 10^{-6}	4.60 x 10^{-6}
Minimum time response (°C)	0	0	0	0
Settling time to zero, s (approximate)	0.00025	0.00025	0.00025	0.00025

CONCLUSION

- The objective of the paper was to investigate the use and tuning of I-P, I-PD and PI-first order compensators to control mold temperature.
- The three compensators are from the second generation of control compensators presented by the author since 2014.
- The three compensators were tuned using the MATLAB optimization toolbox and the best performance index as investigated by the author.
- A PID controller from previous work was compared with the three proposed compensator/controllers.
- The I-PD compensator succeeded to eliminate completely the maximum overshoot of the control system compared with 0.84 % with the PID controller and succeeded to settle after 13 s compared with 10.1 s for the PID controller for reference input tracking.
- The PD-PI controller succeeded to reduce the maximum overshoot of the control system to 0.14 % compared with 0.84 % for the PID controller and succeeded to settle after 9.2 s compared with 10.1 s for the PID controller for reference input tracking.
- The 2DOF-2 controller succeeded to generate step time response for the mold temperature having 0.497 % maximum overshoot compared with 0.84 % with the PID controller and had a relatively small settling time of 6.69 s compared with 10.1 s for the PID controller for reference input tracking.
- The performance of the proposed compensator/controllers regarding disturbance rejection was excellent through the use of a high pass second-order filter receiving the disturbance input. Both maximum time response and settling time to zero were negligible indicating the success of all the presented compensator/controllers to suppress the input disturbance.
- If the interest of the control engineer is to satisfy the condition of minimum maximum overshoot, then the proposed I-PD compensator is the best choice.
- If the interest of the control engineer is to satisfy the condition of minimum settling time, then the proposed 2DOF-2 controller is the best choice.

Dedication

- I dedicate this research work to the Egyptian '***National Plastics Company***' (NPC).
- The reason for this dedication is:
- It was the biggest old plastics company established in Egypt on 1946.
- Its production was in the quality level of world international companies.

- It was awarded the ‘***International Golden Planet Award***’ because of its global level production of plastic products.
- Its profits were the highest among all the working companies in Egypt.
- Its profits were 6.8 million LE in 1976 and 10.4 million LE in 1978.
- I was a witness on its glory during the 1980’s and 1990’s because I was living near its main factory in East Omrania of Giza and I was in regular visits with its ‘***Chairman of Board of Directors***’ during the 1980’s who was an engineer because of my interest in this strategic industry.

- Finally this great national industry was sold in 2005 for only 30 millions LE!
- Sorry:

- Sorry King Farouk who established the NPC.
- Sorry President Abdel-Nasser who encouraged the NPC to be in an international level.
- Sorry Egypt to loose such outstanding successful industry.

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