



Design of Multimodel based MPC and IMC control schemes applied to injection molding machine

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Abstract

Good control of plastic melt temperature for injection molding is very important in reducing operator setup time, ensuring product quality, and preventing thermal degradation of the melt. The controllability and set points of barrel temperature also depend on the precise monitoring and control of plastic melt temperature. Motivated by the practical temperature control of injection molding, this paper proposes MPC and IMC based control scheme. A robust system identification and control methodology is developed which uses canonical varieties analysis for identification and model predictive control for regulation. The injection molding process consists of three zones and the mathematical model for each of the zone is different. The control output for each zone controller is assigned a weight based on the computed probability of each model and the resulting action is the weighted average of the control moves of the individual zone controllers.

Keywords: Injection-Molding Machine (IMM), IMC Control, Temperature Control.

1. Introduction

An injection molding machine generates parts by melting the mold material and injecting it under pressure into the mold cavity where it solidifies to form the product. The major subsystems are hydraulic drive unit, the barrel, and the clamping unit. Temperature control is an important issue in many industrial processes. These processes usually show an integrating response characteristic during the heating up, and after rising to the set point temperature, it tends to behave in a stable manner given a certain heating range, due to air-convection losses. The challenges in these processes are to avoid overheating (to reduce overshoots in temperature) in the heating up stage and to tightly maintain the set-point temperature against load disturbances and process/ambient variations.

An Injection molding machine, also known as an injection press, is a machine used for manufacturing plastic products by the injection molding process. Injection molding is a manufacturing process for producing parts from both thermoplastic and thermosetting plastic materials. It consists of two main parts, an injection unit and a clamping unit. There are four major elements that influence the process. They are molder, material, injection molding machine, and mold. Of these four, the injection machine and the mold are the most varied and mechanically diverse. Most injection machines have three platens and may be electrically operated. Most function horizontally, but there are some vertical models in use. The injection system mechanism may be of the reciprocating screw type or, less frequently, the two-stage screw type. Also included is a hopper, a heated injection barrel encasing the screw, a hydraulic motor, and an injection cylinder. The system function is to heat the thermoplastic to the proper viscosity and inject it into the mold. As the resin enters the injection barrel, it is moved forward by the rotation of the screw. As this movement occurs, the resin is melted by frictional heat and supplementary heating of the barrel encasing the screw. The screw has three distinct zones which further processes the resin prior to actual injection. [3].

Injection is accomplished through an arrangement of valves and a nozzle, all acted upon by the screw and the hydraulic pump that pushes the resin into the mold. This so-called “packing action” occurs at pressures from 20,000 to 30,000 psi and higher. The clamping system’s function is to keep the plastic from leaking out or “flashing” at the mold’s parting

line. The clamping system consists of main hydraulic pressure acting on the mold platens and a secondary toggle action to maximize the total clamping pressure.

Tao Liu, Ke Yao and Furong Gao [1] have used relay feedback test for online identification of the 3 zones of the barrel in an injection molding machine. A united control schemes based on the internal-model-control structure is proposed for heating-up and steady operations against load disturbance. Chris Diduch and Wan Gui Li [2] have developed a first principle model for the injection molding process based on certain assumptions that may be used for the design of a temperature- control system. Dominick V. Rosato [3] explain the injection molding process and the handbook will be used all the research work of Injection molding machine. Rickey dubay, Adam C. Bell [4], have used MIMO and SISO models and Model predictive control strategy used for zone temperature control. Chris Diduch and Wan Gui Li [5] have used Model predictive control strategy for first principle model. J.A. Rossitier [6] have explained the practical approach of MPC used in IMM. Donald E. Gustafson and William M. Lebow [7] have considered the problem of online control and implemented the MPC based on that. Prasanth Ambady [8] works monitored online state variables and control setpoints are generated. T.A. Badgwell S.J qin [9] have presented to nonlinear predictive control and The practical approach of Tuning MPC were explained by Wojsznis .w , Gudaz. J [10]. The heating barrel of an injection molding machine is as shown in Fig.1.

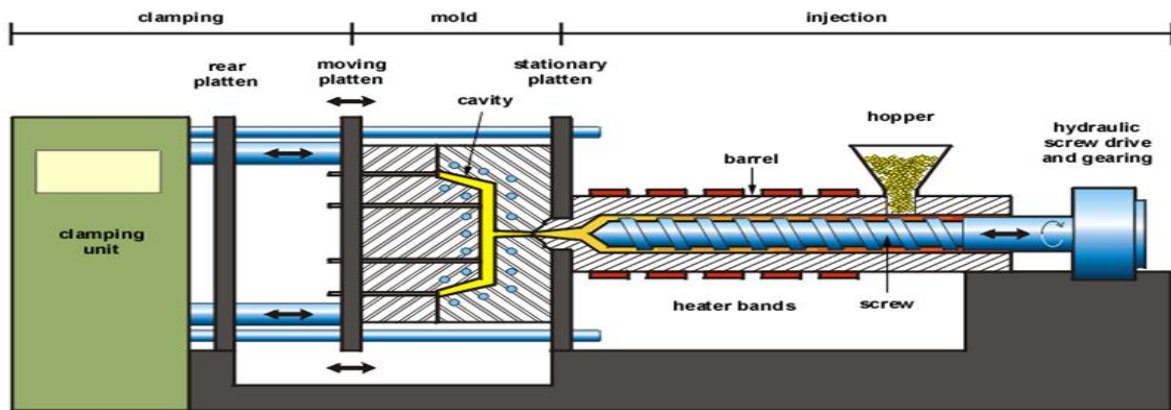


Fig.1: Schematic diagram of Injection Molding machine

2. Theoretical modeling

2.1. Modeling of injection molding machine

To achieve better product quality and control of the many process parameters, there is a requirement for improved temperature control that reduces temperature fluctuations and transients during startup and molding. The dynamics of the IMM that relate heater inputs and barrel or melt temperature are distributed and nonlinear, and depend on a variety of factors that include the type of plastic, the backpressure and screw speed.

Although the temperature is distributed over the IMM, the temperature-control system uses a fixed number of strategically placed heaters and thermocouples, each associated with a particular zone. For the purpose of control system design, the dynamic model that relates heater inputs and temperature within a particular zone and at a particular operating point normally takes the form of a second order linear system with transportation delay.

Assumptions considered for the theoretical modeling:

- No melt temperature gradients exist within the defined zone and the thermocouple reading for each zone represents the temperature for that entire region.
- The polymer that resides between the barrel inner wall and the screw outer surface has constant thermal properties in the radial direction and within each zone, but these vary from zone to zone axially.
- There is perfect thermal contact at the interface of the polymer with the barrel and the screw.
- The heat added by the rotation of the screw and the backpressure is considered negligible compared to that added by the heaters.
- The interaction between the zones is negligible.
- The ambient temperature is constant.

The factors that affect the total heat flux supplied to polymer from each zone can be expressed by a flux balance equation, involving the manipulated variable in its discretized form. This discretization is used here only to demonstrate the true mechanics of energy transfer. Temperature gradients exist within any defined zone length. The energy balance equation can be expressed as:

$$Q_{sup,i} = Q_{conv,i} + Q_{rad,i} + Q_{n,i} \quad (1)$$

Where $i = 1, 2, 3 \dots z$

$Q_{n, i}$ - the component of heat by conduction normal to barrel circumference

$Q_{sup, i}$ - heat supplied by heaters

$Q_{conv, i}$ - heat loss due to convective heat transfer

$Q_{rad, i}$ - heat loss due to radiative heat transfer

The component $Q_{n, i}$ represents the heat flux required to increase the temperature of the barrel, polymer, and screw materials. The convective heat transfer $Q_{conv, i}$ comprises two mechanisms, one due to random molecular motion and the other due to bulk or macroscopic motion of air. IMM's are normally located in an enclosed cell without forced advection. Therefore, convective heat transfer was categorized and modeled as free or natural convection arising from density variations caused by temperature variations in the air.

The radiation heat flux between surface and its surroundings is governed by the Stefan-Boltzmann constant, the thermal emissivity of the surface, the surface geometry, and the surroundings and body temperatures. From these parameters, it can be expressed as

$$Q_{sup, i} = \frac{k \partial T}{\partial t} + h(T_i^4 - T_a^4) + \varepsilon \sigma (T_i - T_a) \quad (2)$$

The energy balance equation is [3]

$$\frac{V I \cos \theta}{2 \pi r \Delta l} = \frac{k \partial T}{\partial t} + h(T_i^4 - T_a^4) + \varepsilon \sigma (T_i - T_a) \quad (3)$$

Where

$V I \cos \theta$ is the power fed to the induction heater

T_i is the temperature at a point in any zone

The specifications of the Injection molding machine is obtained from De-Techno LNC4-E Model IMM available in the laboratory of the Department of Rubber and Plastic Technology, MIT, Chennai, India, and Listed in Table 1.

Table 1: Operating data of IMM process

Process variable	Operating conditions
Temperature (T)	308.15 – 443.15 K
Current (I)	0.08-50 Amps
k (conductivity)	0.1 W/m-K
Radius of barrel	0.015 m
Length of each zone	0.373 m
Heat transfer coefficient	24.5 W/m ² K
T_a	308.15 K
ε	0.75
σ	5.67×10^{-8} W m ⁻² K ⁻⁴

2.2. Design of multimodal

To design the Multimodel based controller, the nonlinear process has been linearized at “n” different operating points and their corresponding transfer function models have been determined.[1] have used relay feedback test for online identification of the 3 zones of the barrel in an injection molding machine. The MPC and IMC controllers are designed based on first principle models and are used to control the non-linear process. The IMM is assumed to have a operating temperature range of 308.15 K to 453.15 K. In order to compensate for the non-linearity, the entire non-linear region is divided into the following linear regions:

- 308.15 to 423.15 K
- $423.15 < T < 433.15$ K
- $433.15 < T < 443.15$ K
- $T > 443.15$ K

Individual multi models are developed for each of these above regions. Accordingly, three individual MPC and IMC controllers are designed one each for the three regions. If the temperature is in the range 308.15 to 423.15 K, the effect of the first controller alone will be felt.

If the temperature is in the range 423.15 to 433.15 K, a combination of the effects of the first and second controller will be felt. If the temperature is in the region 433.15 to 443.15 K a combination of the second and third controller will act and if the temperature is in the region greater than 443.15 K, then the effect of the third controller alone will be felt. The contribution of each controller will be decided by the weights that are generated based on the current temperature reading. The block diagram of multimodel MPC and IMC controller is shown in Fig 2. The MPC controller accepts the scheduling the variable (temperature) as input and computes the controller parameters namely controller gain K_c and Integral time T_i and derivative time T_d at each and every sampling instant.

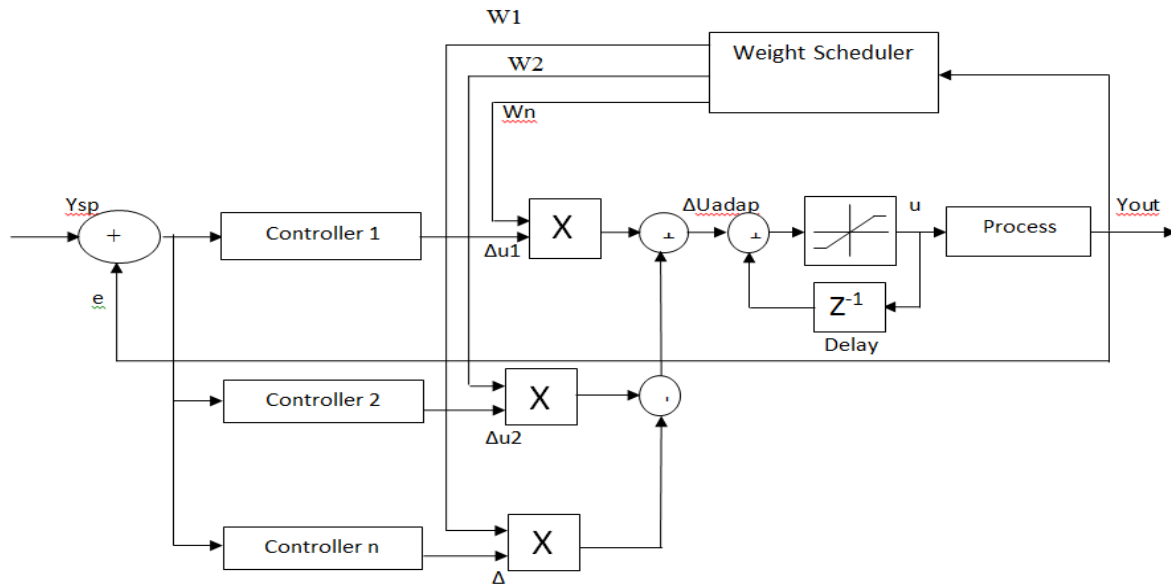


Fig. 2: Block diagram of MM-controller

3. Model predictive controller for IMM

In this section, design of Dynamic Matrix controller for Injection Molding machine has been outlined. MPC is a form of control algorithm in which the current control action is obtained by solving a finite horizon of open loop optimal control problem using the current state of the plant as the initial state. This process is repeatedly done for each sampling point [5]. The optimization yields an optimal control sequence and the first control in this sequence is applied to the plant. In MPC, the models which are used, determine the behavior of complex dynamical systems. The models are used to predict the behavior of dependent variables or outputs of the system with respect to changes in the process independent variables or inputs. Fig. 3 gives the block diagram of the Regulatory MPC.

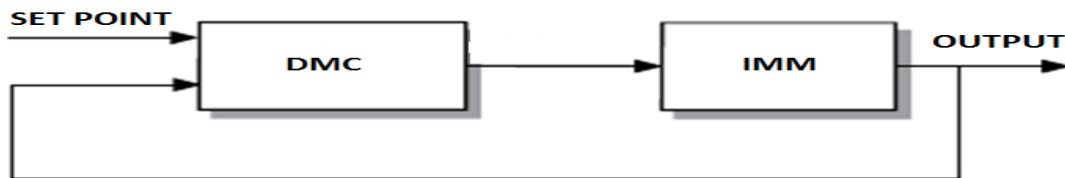


Fig.3: Regulatory DMC

Model Predictive Control method consists of three main components. These are namely:

- 1) Process model.
- 2) Cost function.
- 3) Optimizer.

The process model includes the information about the controlled process and it is used to predict the response of the process values according to manipulated control variables. There after minimization of cost function ensures that the error is reduced. In the last step, optimization techniques are applied and the output gives the input sequence for the next prediction horizon. The basic concept of MPC is illustrated in Fig. 4.

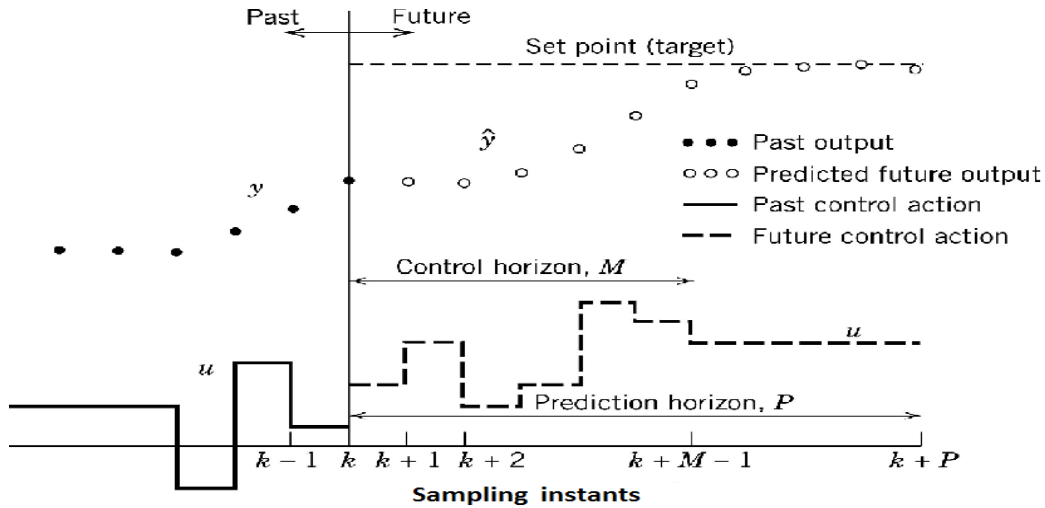


Fig.4: Basic concepts of MPC

$$Y(k+1) = y_0 + S_i \Delta u(k-i+1) + S_N u(k-N+1) \tag{4 a}$$

Where $i = 1 \dots N-1$

S_i = the i -th step response coefficient

N = model length

y_0 = initial value at $k=0$

If $y_0=0$, this one-step-ahead prediction can be obtained from Eq. (4a) by replacing $y(k+1)$ with $\hat{y}(k+1)$

$$\hat{y}(k+1) = y_0 + \sum_{i=1}^{N-1} S_i \Delta u(k-i+1) + S_N u(k-N+1) \tag{4b}$$

Equation (4b) can be expanded as:

$$\hat{y}(k+1) = \underbrace{S_1 \Delta u(k)}_{\text{Effect of current control act}} + \underbrace{\sum_{i=2}^{N-1} S_i \Delta u(k-i+1) + S_N u(k-N+1)}_{\text{Effect of past control actions}}$$

Similarly, the j -th step ahead prediction is Eq. (4c)

$$\hat{y}(k+j) = \underbrace{\sum_{i=1}^j S_i \Delta u(k+j-i)}_{\text{Effect of current future control act}} + \underbrace{\sum_{i=j+1}^{N-1} S_i \Delta u(k+j-i) + S_N u(k+j-N)}_{\text{Effect of past control actions}} \tag{4c}$$

The predicted unforced response is

$$\hat{y}_o(k+j) = \sum_{i=j+1}^{N-1} S_i \Delta u(k+j-i) + S_N u(k+j-N) \tag{4 d}$$

Eq (4c) is written as:

$$\hat{y}(k+j) = \sum_{i=1}^j S_i \Delta u(k+j-i) + \hat{y}_o(k+j) \tag{4 e}$$

$$Y_o(k+1) = \text{col}[\hat{y}_o(k+1), \hat{y}_o(k+2), \hat{y}_o(k+P)] \tag{4 f}$$

$$\Delta U(k) = \text{col}[\Delta u(k), \Delta u(k+1), \dots, \Delta u(k+M-1)] \tag{4 g}$$

The model predictions in Eq (4e) can be written as:

$$Y(k+1) = S \Delta U(k) + Y_o(k+1) \tag{4 h}$$

$$S = \begin{bmatrix} S_1 & 0 & \dots & 0 \\ S_2 & S_1 & 0 & \vdots \\ \vdots & \vdots & \ddots & 0 \\ S_M & S_{M-1} & \dots & S_1 \\ S_{M+1} & S_M & \dots & S_2 \\ \vdots & \vdots & \ddots & \vdots \\ S_P & S_{P-1} & \dots & S_{P-M+1} \end{bmatrix}$$

3.1. Bias corrections

The model predictions can be corrected by utilizing the latest measurement, $y(k)$. The corrected prediction is defined to be:

$$\hat{y}(k+j) = y(k+j) + [\hat{y}(k) - y(k)] \quad (4\ i)$$

Adding this bias correction to each prediction

$$\hat{Y}(k+1) = S \Delta U(k) + \hat{Y}_o(k+1) + [y(k) - \hat{y}(k)] \quad (4\ j)$$

Where

$$\hat{Y}(k+1) = \text{col}[\hat{y}(k+1), \hat{y}(k+2), \dots, \hat{y}(k+P)] \quad (4\ k)$$

3.2. MPC tuning

Every controller design has some design parameters, which can be tuned to get the desired response of the controller. These parameters are called the tuning parameters of the controller. The following guidelines are basically used to tune a MPC:

- 1) The model length (N) should be selected so that $N\Delta t \geq$ open loop settling time. Values of N are normally taken between 20 to 70.
- 2) The prediction horizon determines how far into the future the control objective reaches. Increasing prediction horizon makes the control more accurate but increases the computation. The most recommended value of prediction horizon is when prediction horizon = Model length + Control horizon.
- 3) The control horizon determines the number of the control actions calculated into the future. Too large value of the control horizon causes excessive control action. Small value of the control horizon makes the controller insensitive of noise.

4. Internal model controller for IMM

The IMC structure compensates for disturbances and model uncertainties. The IMC tuning (filter) factor “ λ ” is used to detune for model uncertainty [10]. The standard IMC design procedure is focused on set point responses.

IMC design procedure

The various steps in the Internal Model Control (IMC) system design procedure are:

Factorization

A transfer function is separated into invertible and non-invertible portions. The factor containing right hand plane (RHP) or zeros or time delays become the poles in the inverts of the process model when designing the controller. So this is non-invertible portion which has to be removed from the system.

Mathematically it is given as

$$G_p(s) = G_p^+(s) G_p^-(s)$$

Where

$G_p^+(s)$ is non-invertible portion

$G_p^-(s)$ is invertible portion

Ideal IMC controller

The IMC controller is the inverse of the invertible portion of the process model. It is given as :

$$Q_C(s) = [G_p^-(s)]^{-1}$$

Adding filter

To make the controller proper mathematically it is given as:

$$Q_C(s) = Q_C(s) f(s) = [G_p^-(s)]^{-1} f(s)$$

Where $f(s)$ is a low pass filter.

Low pass filter $f(s)$

In order to improve the robustness of the system the effect of model mismatch should be minimized. Since mismatch between the actual process and the model usually occur at high frequency end of the systems frequency response, a low pass filter $f(s)$ is usually added to attenuate the effects of process model mismatch.

The internal model controller is usually designed as the inverse of the process model in series with the low pass filter.

$$Q_c(s) = Q_c(s) f(s) = [G_p^-(s)]^{-1} f(s)$$

Where $f(s) = 1/(\lambda s+1)^n$

Where λ is the filter tuning parameter to vary the speed of the response of closed loop system.

Now the low pass filter can be of three types:

a) For good set-point changes, the form of filter used is

$$f(s) = 1/(\lambda s+1)^n$$

Where n is the order of the process.

b) For good rejection of step input load disturbances the filter of the form $f(s) = (\gamma s + 1) / (\lambda s + 1)^n$ is used. Where γ is any constant.

5. Simulation results

In all simulation runs, the process is simulated using the nonlinear first principles model equation and the true state variable computed by solving the nonlinear differential equation using differential equation solver in matlab7.0. The entire simulation has been performed with the initial condition given by $T=308.15k$ and $I=2Amps$.

5.1. DMC controller

Three individual DMC controllers are designed one each for the three regions. If the temperature is in the range 308.15 to 423.15 K, the effect of the first controller alone will be felt. If the Temperature set point is 423.15k the weight of the first controller output will be 1. Temperature is in the range 423.15 to 433.15 K, a combination of the effects of the first and second controller will be felt. If the Temperature set point is 433.15k the weight of the first controller output will be less and the second controller weight will be high. If the Temperature is in the region 433.15 to 443.15 K a combination of the second and third controller will act and if the Temperature is in the region greater than 443.15 K, then the effect of the third controller alone will be felt. The contribution of each controller will be decided by the weights that are generated based on the current temperature reading. In order to access the tracking capability of designed controllers, set point variations have been produced. From the response it can be inferred that, all the controllers designed for the injection molding barrel are able to maintain the desired barrel temperature. The results of the Control variable, Controller output for the three zones for Dynamic Matrix Controller structure are shown in Fig 5, 6, 7. The performance criteria of the Internal Model Controller are given in Table 2.

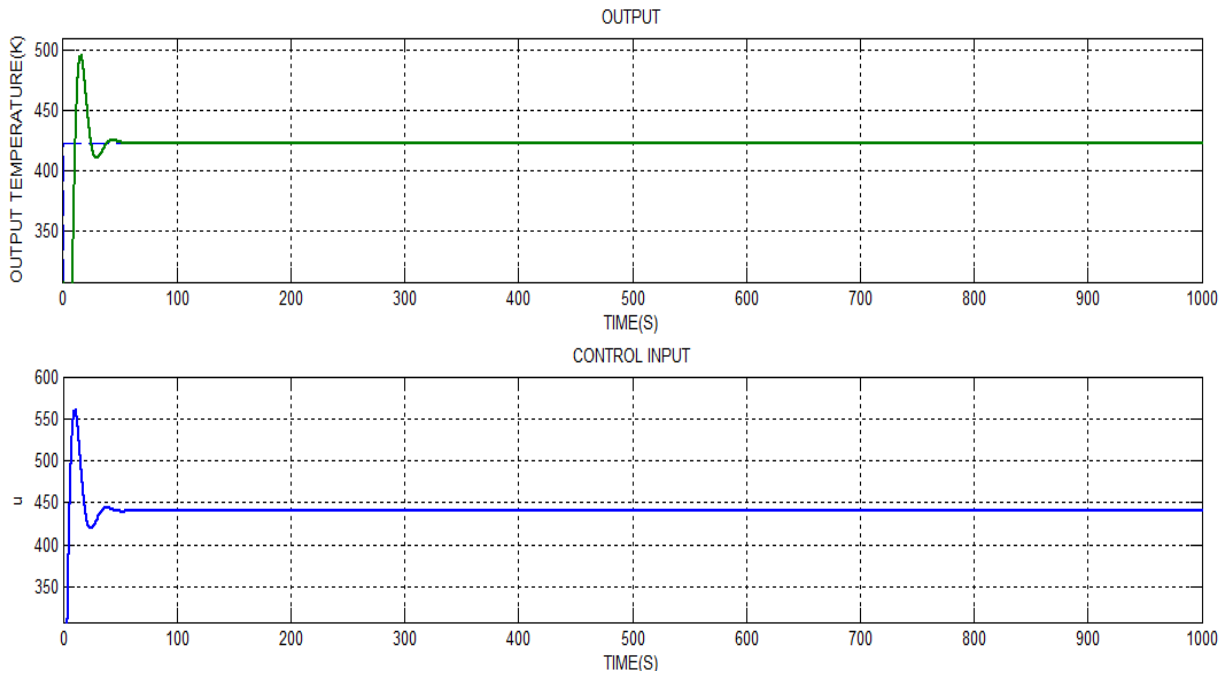


Fig. 5: Closed loop response for a set point of 423.15 K (Zone 1)

Table 2: Performance criteria for DMC controller

Zone	IAE	ISE	Settling Time(s)
Z1(423.15K)	2.3233×10^4	5.3975×10^8	120.8
Z12(433.15)	2.0157×10^4	4.0630×10^8	95.3
Z23(443.15)	4.9869×10^4	2.4869×10^8	203.1

5.2. Internal model controller

The process is simulated with the Internal Model controller .If the temperature is in the range 308.15 to 423.15 K; the effect of the first controller alone will be felt. If the Temperature set point is 423.15k the weight of the first controller output will be 1 and the closed loop response is shown in Fig 8.

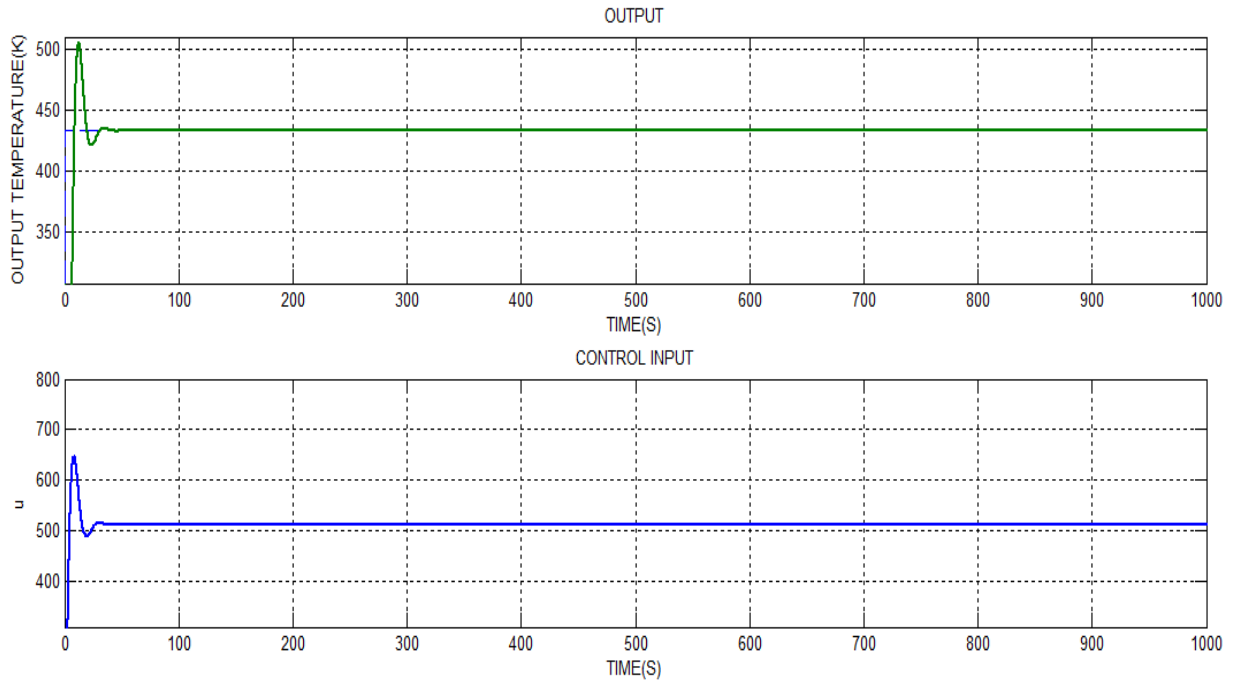


Fig. 6: Closed loop response for a set point of 433.15 K (Zone 2)

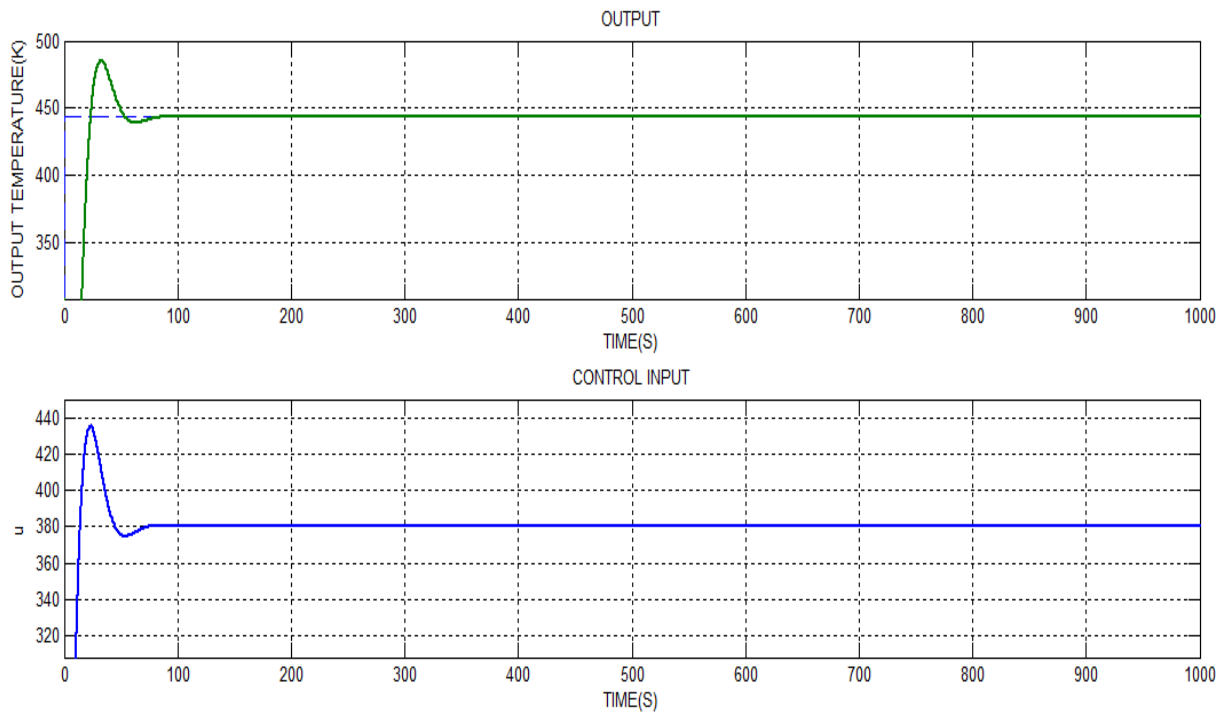


Fig. 7: Closed loop response for a set point of 443.15 K (Zone 3)

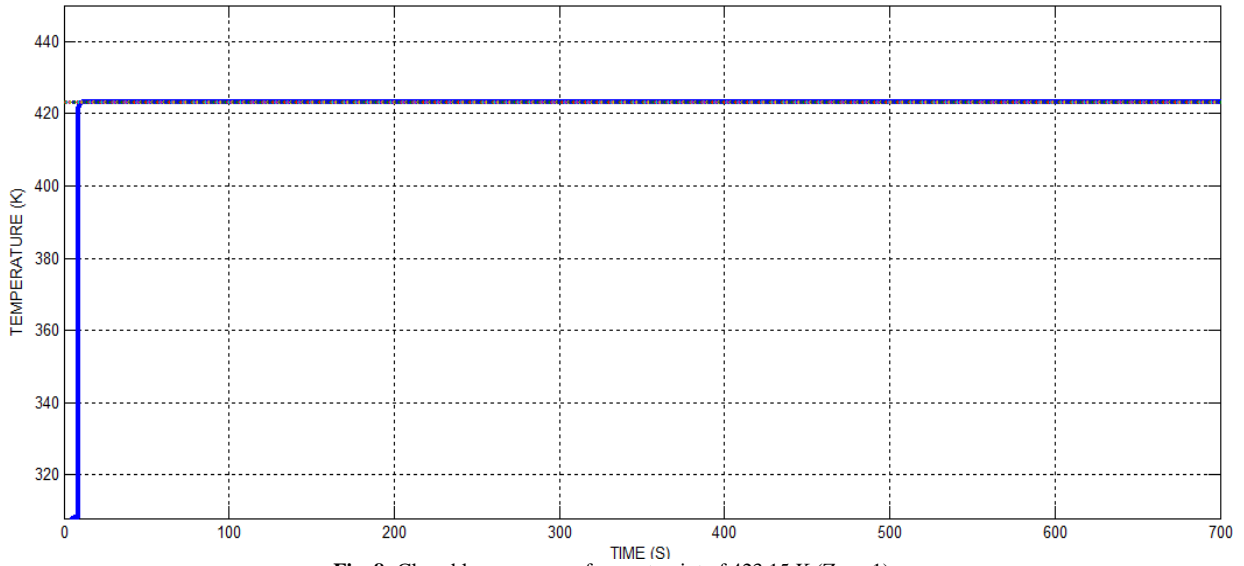


Fig. 8: Closed loop response for a set point of 423.15 K (Zone 1)

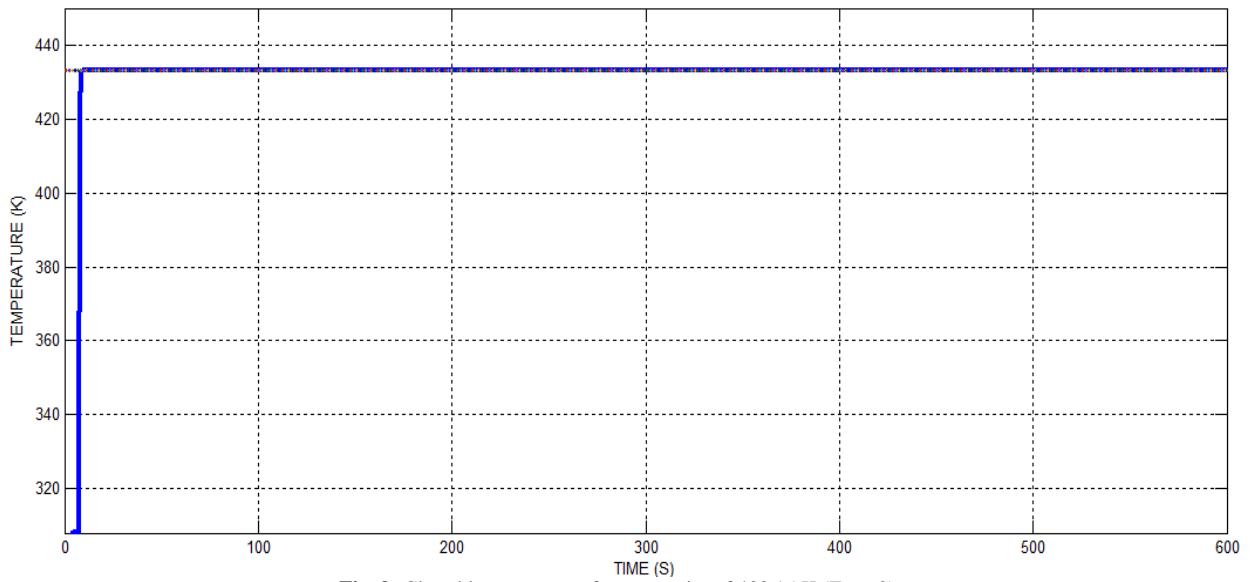


Fig. 9: Closed loop response for a set point of 433.15 K (Zone 2)

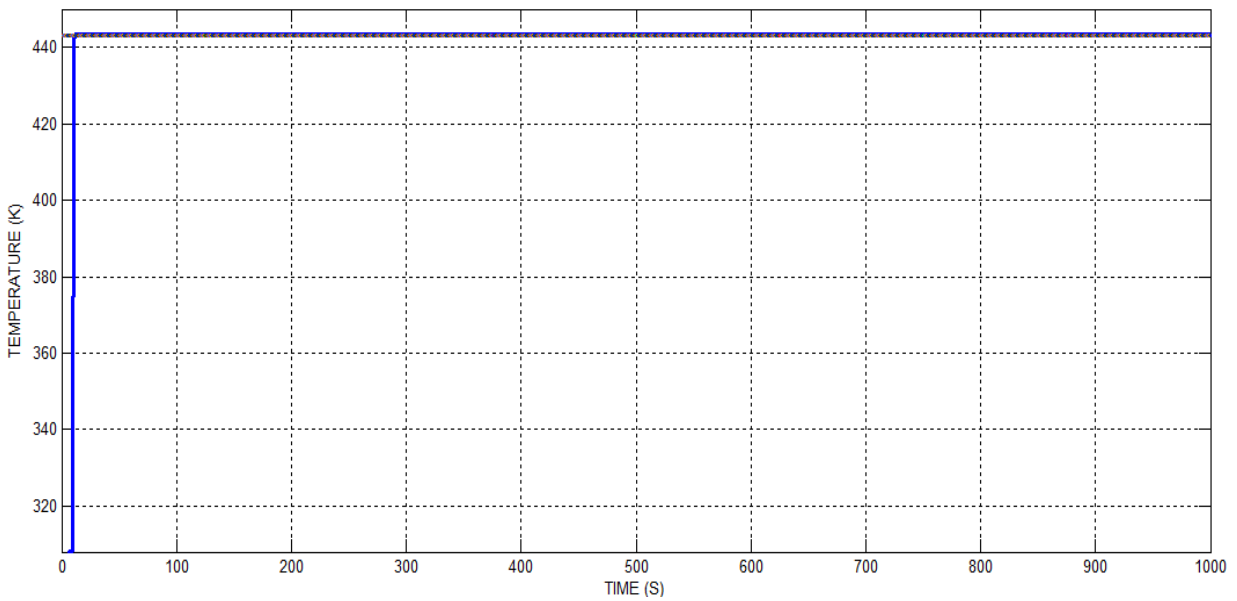


Fig. 10: Closed loop response for a set point of 433.15 K (Zone 3)

Table 3: Performance criteria for IMC controller

Zone	IAE	ISE	Settling Time(s)
Z1(423.15K)	1.698×10^4	2.884×10^8	1120
Z12(433.15)	1.241×10^4	1.54×10^8	1035
Z23(443.15)	2.544×10^4	6.472×10^8	1265

The performance criterion of the Internal Model Controller is given in Table 3. If the Temperature set point is 433.15k the weight of the first controller output will be less and the second controller weight will be high and the closed loop response is shown in Fig 9. If the Temperature set point is 442.15k the weight of the first controller output will be Zero and the second controller weight will be less and third controller will give control action and the closed loop response is shown in Fig 10. The responses of the control variable and control output of the three temperatures zones using Internal Model Controller are presented in Figures 8, 9, 10, respectively.

5.3. Comparison between responses of MPC and IMC

The closed loop responses of the MPC and IMC for all the 3 zones are compared. If the Temperature set point is 423.15k, the weight of the first controller output will be 1 and the closed loop response of two controllers shown in Fig 11. The Temperature set point is 433.15k the weight of the second controller output will be 1 and the closed loop response of two controllers shown in Fig 12. The Temperature set point is 443.15k the weight of the third controller output will be 1 and the closed loop response of two controllers shown in Fig 13.

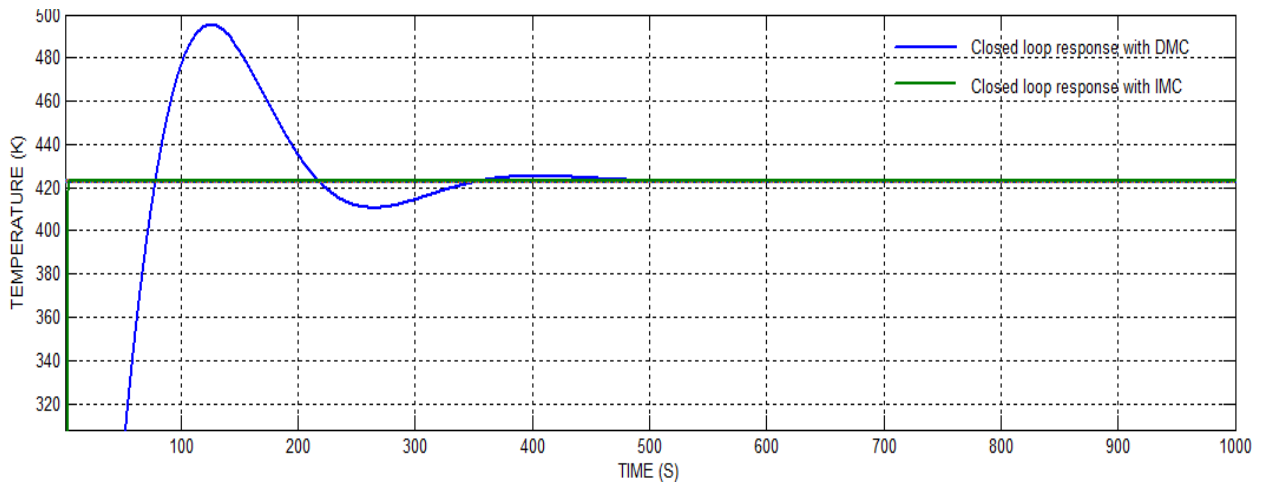


Fig. 11: Closed loop response for a set point of 423.15 K (Zone 1)

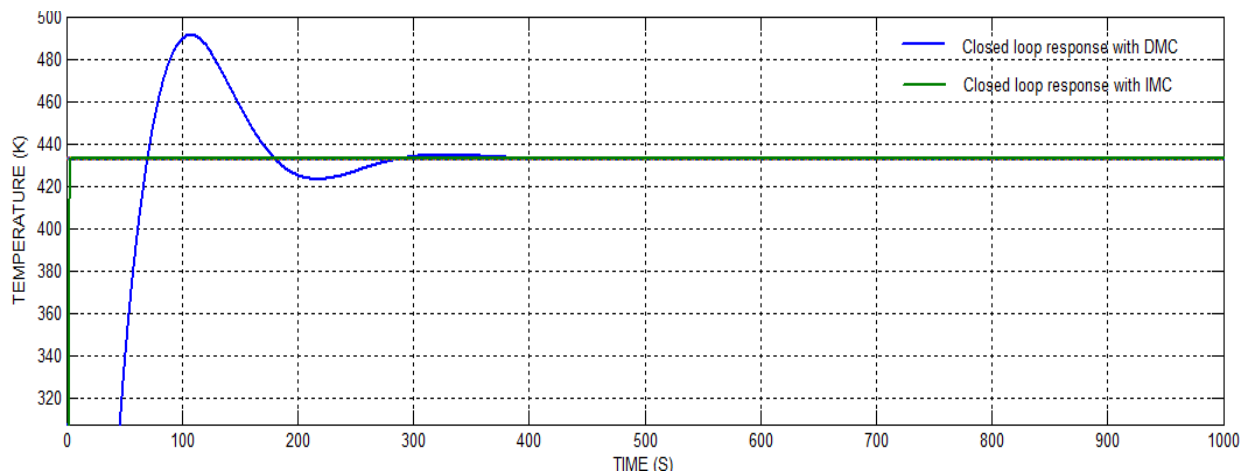


Fig. 12: Closed loop response for a set point of 433.15 K (Zone 2).

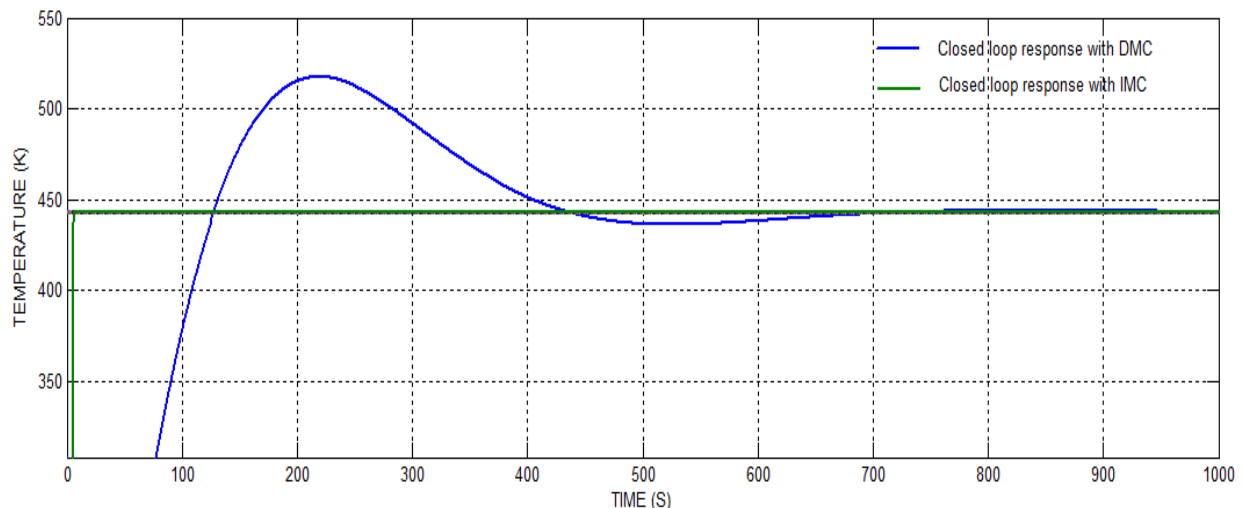


Fig. 13: Closed loop response for a set point of 443.15 K (Zone 3)

6. Summary

The Internal Model controller has a longer settling time than the Dynamic Matrix controller. The IAE and ISE of the IMC are smaller than that obtained from DMC. The DM control yields a better settling time, but it gives rise to large overshoots. In this work the simulation results are obtained from the mathematical model of the heating zones of the barrel. Using the Simulink model of three temperature zones, the temperature response is obtained by manipulating heater current.

Model based control schemes are applied to control the barrel temperature to achieve better performance. Three different controllers have been designed and implemented for injection molding process. The performance of DMC and IMC is analyzed. It has been shown by simulation that Model based methods can also be used to design a controller for typical nonlinear processes. The more accurate the model is as against the plant model, a better response can be obtained. The Internal Model controller has a longer settling time than the Dynamic Matrix controller. The IAE and ISE of the IMC are smaller than that obtained from DMC. The DM control yields a better settling time, but it gives rise to large overshoots which may cause a severe loss of the mechanical properties of the polymer inside the barrel.

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