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Empirical Modelling and Controller Design for an Electrically Heated Oven

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Abstract: ***Temperature control is one of the most fundamental entity in process industries ranging from power generation, Healthcare, laboratories to food processing and beyond. Depending on the intensity of the process various control techniques are used to monitor and regulate the temperature within desired limits to ensure safety and quality.***
This paper deals with modelling and control of an electrically heated oven available in standard control laboratories. The system model is estimated and validated using system identification tool-box and graphical method. PI controller based smith predictor and Internal Model Controller is used as a controller for the system. Performance comparison is done between the controllers practiced to the system in MATLAB Simulink environment. Results suggest that Internal model based controller depict better time domain characteristics in contrast with Smith predictor based controller followed by the classical Ziegler Nichols based PID controller.
Keywords: PID, Smith predictor, Oven, IMC controller, Zeigler Nichols, IDENT toolbox, Empirical modelling.

1. INTRODUCTION

Ovens are thermally insulated boudoir commonly used in various applications feeding from industrial environment to standard laboratories in various disciplines. Most of the applications involving heating generally have precise temperature requirements. Depending on the type and gravity of the applications namely pharmaceutical applications where accuracy demands are very high to test laboratories, food processing and several other, various types and sizes of ovens are used. Shortcomings in accuracy may result in inaccurate results, energy losses and much more. Also depending on the nature of the application numerous type of ovens are used. Commonly six major types of ovens are used in the industrial environment which include applications like baking, curing, drying, cooking, heating, clean room ovens and so on. Each of these type of ovens have dedicated applications and cannot be switched. Now owing to the facts it can be saidthat temperature control is an integral entity in process industry, therefore the need of a control system to regulate the temperature becomes obvious. Time delay also called as dead time is undeniable in many industrial processes including heating applications and is a prime cause of poor stability of the process. Heating applications typically inherit process delay. Systems having dead time require certain amount of time to first see the change in the output to an applied input i.e. the output lags behind input by an interval of time Although a variety of advanced and new types of controllers have been developed in recent years, most common control strategy used is PID control due to its simplicity and robust nature. But since standard PID based controllers don't quite well satisfactorily control processes with large dead time, model based and predictive approach are tested in this paper in their crude form. In this paper controller for a standard electrically heated oven which can reach 100-105 degree Celsius temperature with 230VAC power supply is designed. In [1] a fuzzy adaptive PID control method is presented based on the immune regulating law to control a coke oven's temperature, results show feasibility of the control proposed. Research [2] shows that system characteristics of gas fired oven make it difficult to obtain satisfactory transient response without properly tuning the PID gains. Also the results show superiority of Skogestad tuning methods over the classical Ziegler Nichols tuning method. In [3] a high precision temperature control system based on PID algorithm has been proposed, results suggest its usefulness in practical systems of agriculture and industry. Also [4] has introduced fuzzy control system for an electric heating stove. Comparison done between fuzzy system and PID control show better characteristics obtained by fuzz system. Also in [5-6], [8] shows application of Ziegler Nichols algorithm and various other methods for tuning of PID controller applied to the system. In [7] a heating furnace temperature control based on PLC has been introduced using PID function available in many PLC controllers. In [9] a closed loop system has been designed to control electric stove temperature using PID algorithm and PWM technique. Results show that system has good robustness and precision. Research [10] shows model based controllers for temperature control of ovens. In [12] temperature control of an electric furnace based PID genetic algorithm. Simulations show that optimization algorithm has properties of no overshoot and has quick response. Reference [13] shows design of PID temperature control system based on lab view. Also reference [14] shows application and comparison of SPID and smith predictive control. In [15] 2DOF PID controller has been applied for obtaining better results than 1DOF PID controller. Reference [17] shows design of first order and second order model by multi scale control technique and comparison is done against conventional method. Reference [16], [18] design of PID controller for delay processes and a novel tuning method for IMC controller respectively. Reference [19] shows IMC based process model approach to design a PID controller for a DC motor in real time and its performance comparison is done against Zeigler Nichols tuning. In [20] model based IMC controller for dead time processes has been introduced. The model is developed using step response method.
The rest of the paper is structured overall as follows, section 2 deals with modelling of the system while section 3 deals with designing of controller for the system. Section

4 is concerned with simulations and results and section 5 concludes the paper.

2. SYSTEM IDENTIFICATION AND MODELLING

2.1 System Description

The system under review is a standard electrically heated hot air oven that can reach up to 100-110 degree Celsius using 230V single phase AC power supply shown in figure 1. These types of oven generally find many applications in number of laboratory applications. The table 1 below showcases the specifications of the same.

Table 1:Specifications of the system

Sr.no	Parameter	Value
1	Capacity	85 L
2	Amperage	12.5 A
3	Depth	14 in
4	Ports exhaust	3
5	Temperature	100-110℃
6	Type	Gravity convection. Lab drying and sterilization.

Figure 1standard Laboratory oven

2.2 Methodology

Numerous modelling techniques are used to model applications in process control. The models developed based on underlying physics, chemistry or first principles of the system are known as theoretical models or white-box models. As the complexity of the systems go on increasing it becomes hard to develop theoretical models and the choice of empirical modelling also referred to as black-box modelling or data driven modelling becomes obvious. The general steps to develop an empirical model are shown in figure 2. To develop an empirical model it is necessary to have steady state or transient response of the system, which is obtained experimentally. The obtained responses are used as estimation and validation data to modelling. Generally there is a trade-off seen between model fidelity and cost. As the model fidelity increases the cost also increases correspondingly. Therefore, a balance between model fidelity and cost is to be chosen based upon the gravity of the application. In this paper we choose to develop a continuous time transfer function using time domain data. The model aimed to estimate is a linear process model.

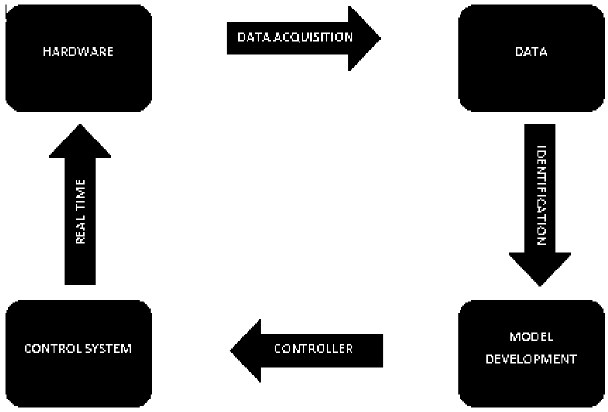

Figure 2 Flow Chart

2.3 System Modelling

2.3.1 Data Gathering

The experimentally obtained data from the system is shown in figure 3 below. The input to the system is Voltage and the output is temperature. The steady state response of the system is obtained by applying a step input to the system. The response change in temperature with respect to time is then obtained and is used as data to estimate a model.

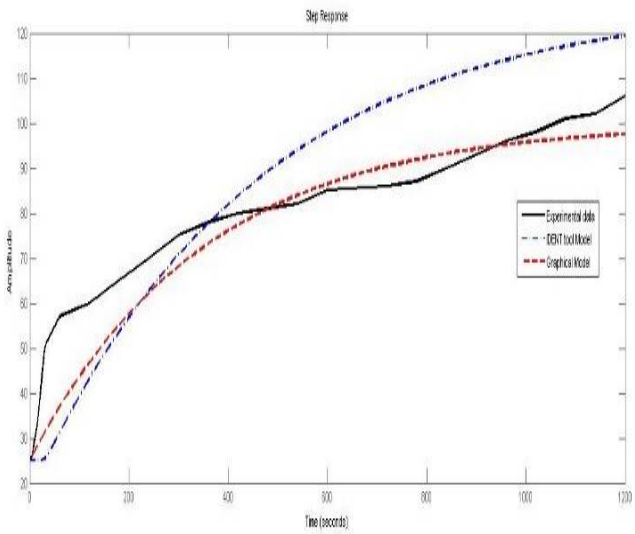

Figure 3 Experimental data v/s obtained model

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2.3.2 Model Estimation and Validation

The IDENT window is shown below in figure 4 below. The obtained input output data is then preprocessed i.e. de-trending and range selection and two sets of data namely estimation data and validation data are formed. In this window form and order of the model can be selected and developed using estimation data accordingly. The models obtained may show up to cent percent fit to estimation data set but does not guarantee to capture the dynamics of the system sufficiently. Therefore the obtained model is then validated against various data sets to obtain its percentage fit to the experimental data.

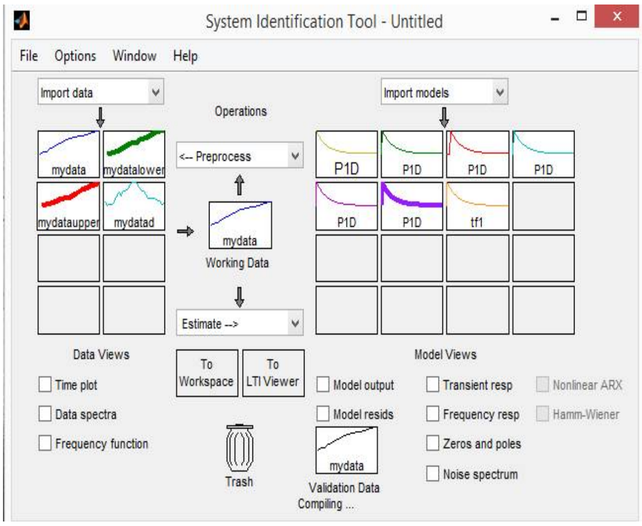

Figure 4 IDENT window

Figure 5 below shows the percentage fit of models of various forms and order to estimation data and validation data. Thus, the validated model having good fit can be finalized for further evaluation. The model that have good percentage fit to both estimation and validation data is chosen and finalized. In this case first order process model with delay shows highest fit to both estimation and validation data.

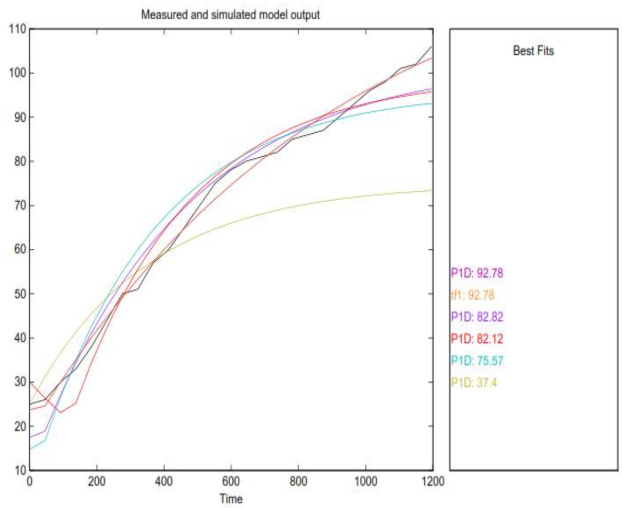

Figure 5 Percentage fit of models developed to data

2.3.3 Model Finalization and Response Plotting

The finalized model is then subjected to step input and its open loop response is plotted along with its pole zero plot using the IDENT toolbox. Figure 6 and figure 7 which show step response and pole zero plot of the system model respectively. The pole-zero plot of the system reveal that the system is marginally stable since the pole lie at the origin Figure 3 shows fit of model developed using the IDENT toolbox in MATLAB and graphical method with the experimental data. The graphical method includes manually assessing the data to find the order of the transfer function and parameters like DC gain which is the steady state value, time constant which is time mark of 63% of final value, number of poles and zeros and time delay for developing a FOPDT or SOPDT model. A first order system consists of only one real pole and no zeros at all. Based on the results the identified first order time delay transfer function model is given by equation 1 below

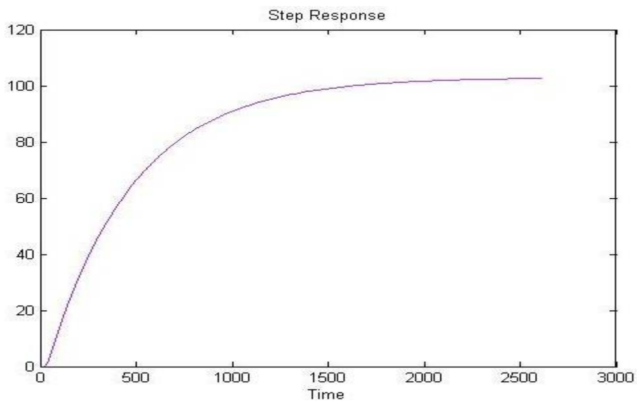

Figure 6 Step response of the obtained model

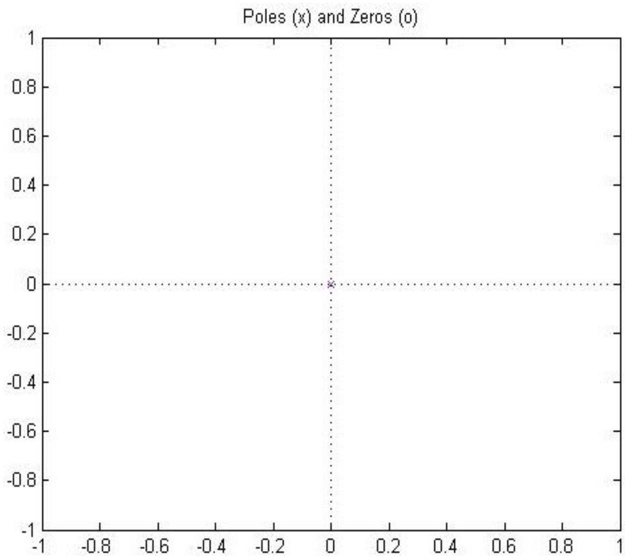

Figure 7 Pole zero plot of the obtained model

$$G(s) = \frac{75}{350s+1} e^{-32s} \qquad (1)$$

Where,

Input = Voltage (V)

Output = Temperature (℃)

3. CONTROLLER DESIGN

This section deals with selection and design of controller for the system. The obtained model of the system is FOPDT in nature and thus has delay which is fairly large. Delay is the time between when the controller applies input and its effect is first observed in the output. Although time delay are common in many industrial processes it is quite difficult to control such processes with conventional controllers and thus need advancement in control strategy. This problem can be solved by using model predictive controllers which are also referred to as time delay compensators. The following control strategies listed below as Ziegler Nicholas PID controller (Z-N PID), Smith Predictor controller (S-P PID) and Internal Model controller (IMC) are applied to overcome the problem.

3.1 Z-N PID

The Ziegler Nichols tuning method is one of the oldest and classical methods to tune a PID controller developed in (1942). Although the resulting tuning parameters are slightly on the aggressive side provide good starting point for fine tuning. The time delay model can be easily approximated to a higher model with no time delay using the pade dead time approximation. The accuracy can be increased by increasing the order of approximation. Figure 8 shows MATLAB Command window to obtain pade approximation of the delay present in the derived system transfer function. The approximation of fourth order quite well matches the original FOPDT model.

```
MATLAB Command Window                                    Page 1

>> s=tf('s');
>> Plant=(exp(-32*s)*(75))/(350*s+1);
>> stepplot(Plant);
>> hold
Current plot held
>> p1=pade(Plant,4)
stepplot(p1)

p1 =

        75 s^4 - 46.87 s^3 + 13.18 s^2 - 1.923 s + 0.1202
  ---------------------------------------------------------------
  350 s^5 + 219.7 s^4 + 62.15 s^3 + 9.148 s^2 + 0.5864 s + 0.001602

Continuous-time transfer function.

>>
```

Figure 8 Delay approximation command MATLAB

The figure 9 show step response of the approximated model and FOPDT model. It can be seen that the response is quite similar and thus suggests that the approximated model and the FOPDT model can be used interchangeably. The fourth order approximate model is then tuned in a closed loop using Ziegler Nichols method 1 using the MATLAB command given in [24]. The resulting PID controller has values given in table 2 below.

Table 2: Z-N PID parameters

Sr.no	Parameters		
	Kp	***Ki***	***Kd***
1	0.1776	0.002763	2.85376

The PID controller tuned with the values given in table 2 is applied simultaneously to approximate and FOPDT model as shown in figure 10 and the responses overlap showing accuracy of the approximation.

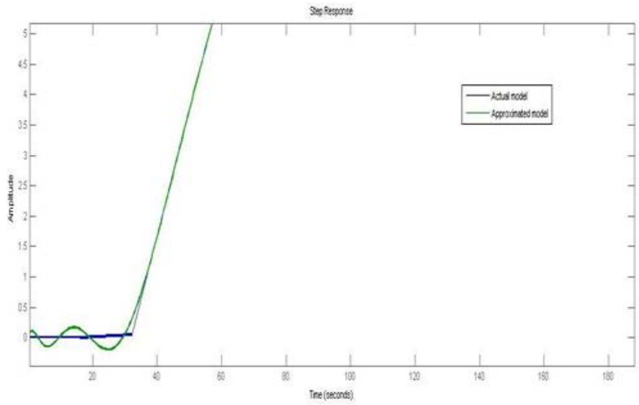

Figure 9 Step response of FOPDT and approximate model

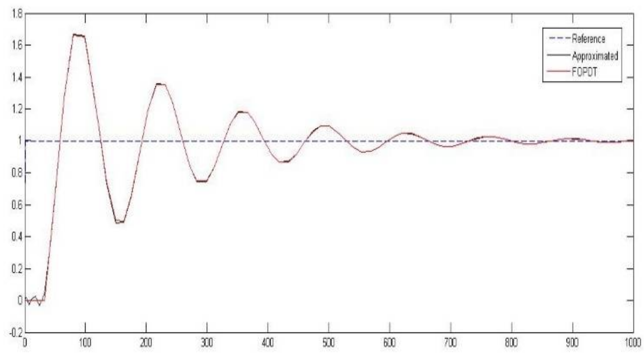

Figure 10 Closed loop response of FOPDT &pade model

The Simulink model of the Z-N PID controller used is shown in figure 11 below. Both PID controllers are identical in both models and have same tuning parameters.

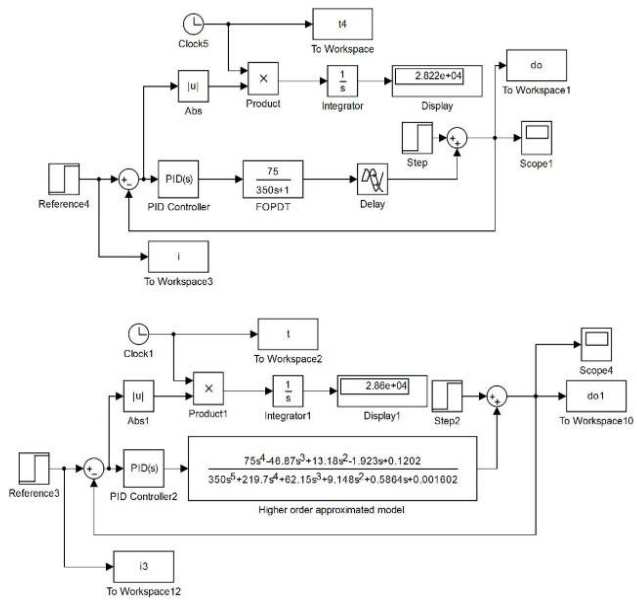

Figure 11 Simulink model of Z-N PID controller

3.2 S-P PID

A smith predictor is a time delay compensation / predictive controller technique which is used to control processes with large dead time [30]. It was invented by O. J. M. Smith in the year (1975). The structure of the smith predictor compensator can be divided into two parts namely the controller part and predictor part. It is one of the standard tool that can handle dead time. The compensator works on principle of ruling out the dead time effect from the system. The Simulink model used to implement the compensator is show in figure 12 below. The inner loop consists of the approximated model and the outer loop consists of FOPDT model. The PID controller in the main loop is tuned with the same values as suggested in table 2.

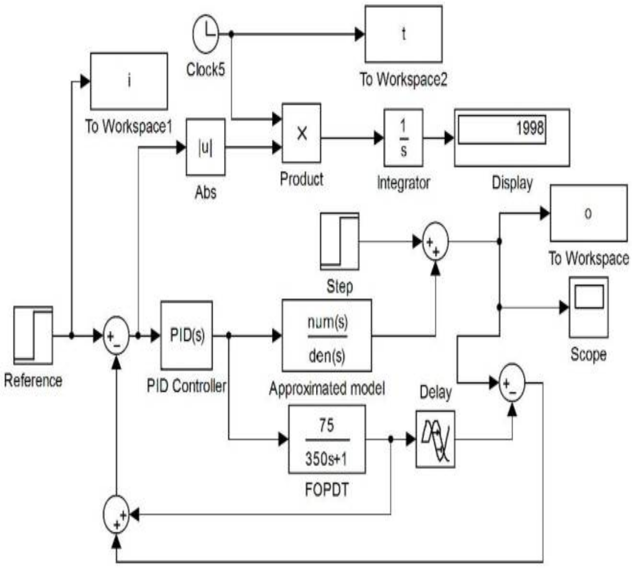

Figure 12 Simulink model of S-P PID controller

3.3 IMC

The Internal model controller method was introduced by B. A. Francis and W. M. Wonham in the year (1976). In this technique a process model is fed in parallel with the actual plant. The difference output of the both blocks is fed back into the controller [23]. It works on the principle that plant model cancels out the delay caused by the plant itself. The Simulink model used to implement the internal model controller is shown in figure 14 below. The resulting controller is given by equation 2 below which as lambda as a tuning parameter as a trade-off between robustness and set point tracking. After many manual iterations it is found out that λ = 2 provide good response and is therefore used in simulation. Figure 13 shows response of system for various values of lambda.

$$Gc(s) = \frac{350s+1}{\lambda * 75s+75} \quad (2)$$

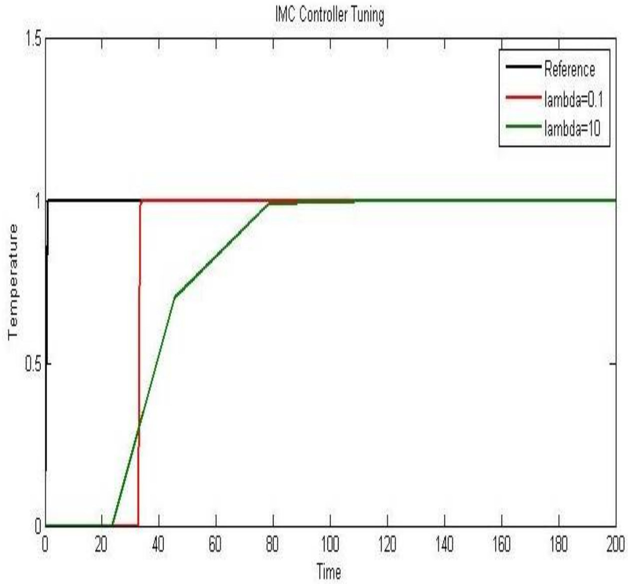

Figure 13 Simulink model of IMC controller

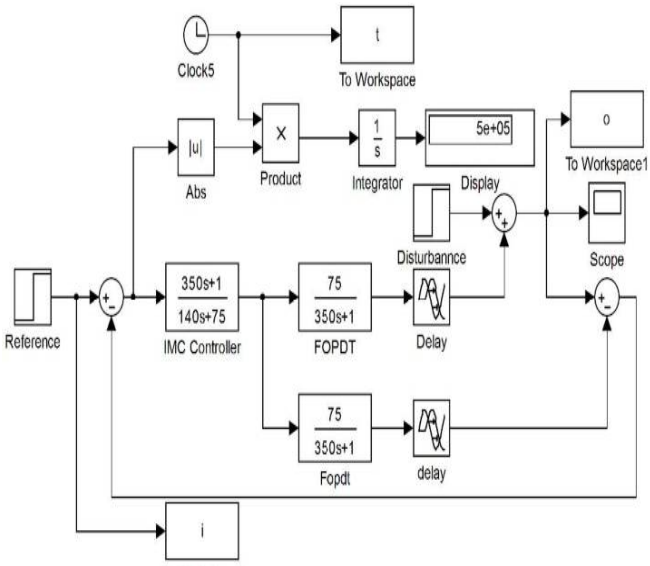

Figure 14 Simulink model of IMC controller

4. Simulation Results

The closed loop response is obtained by application of controllers and tuning them as per design. The smith predictor and IMC controller show better response as compared to Z-N PID. Also a delay can be seen in the response. To obtain the disturbance rejection graph a step input of 0.3 amplitude is injected into the system output at time interval of 500 seconds IMC shows better response as compared to smith predictor and Z-N PID. For set point tracking a square wave signal of 0.006 HZ is used. The response of IMC is good in comparison with Z-N PID and smith predictor. The details of some of the time domain characteristics are given in table 3

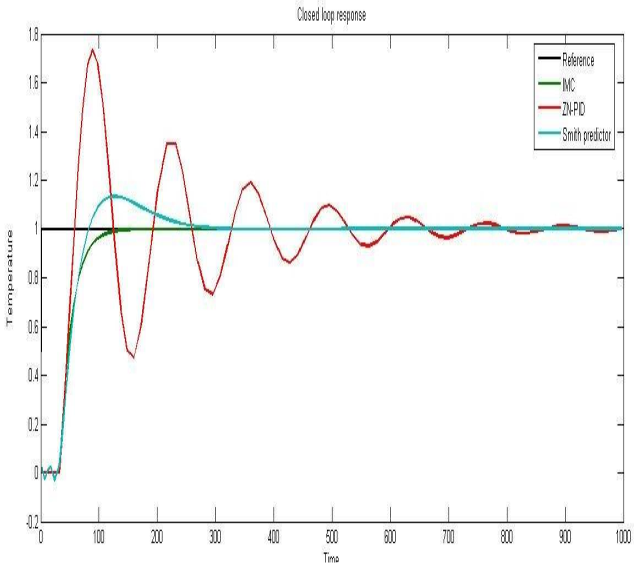

Figure 15 Closed loop response

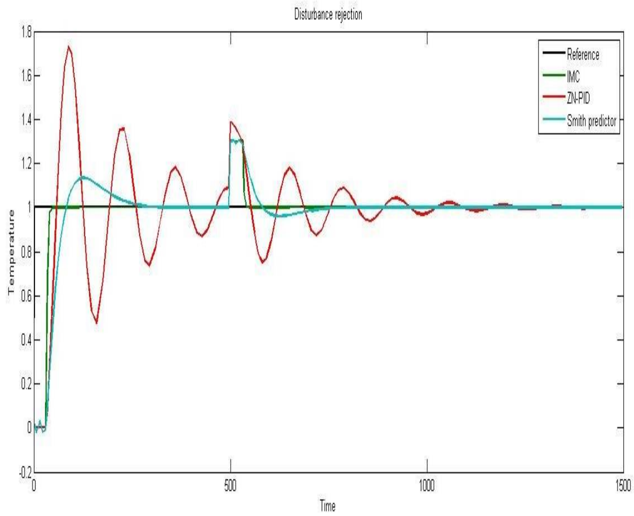

Figure 16 Disturbance rejection

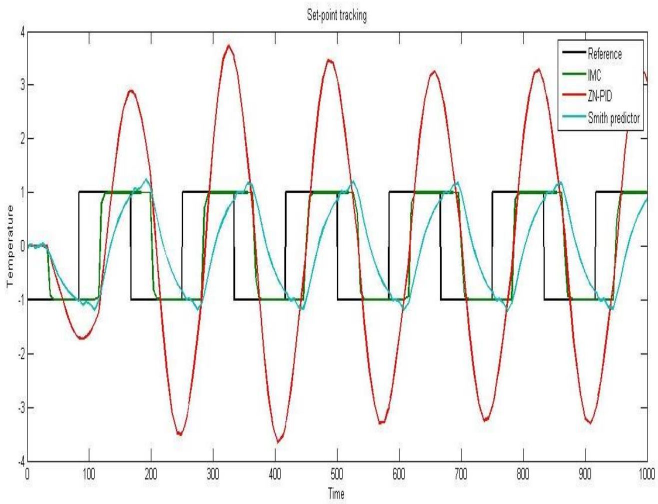

Figure 17 Set-point tracking

Table 3: Controller characteristics comparison

Characteristics	**Controllers**		
	Z-N PID	***S-P PID***	***IMC***
Rise time (s)	20.1	37.2	4.1008
Settling time (s)	776	212	39.3043
Overshoot (%)	72.9	13.5	0.00018
ITAE	2.8e+04	1998	5e+05
Peak response	1.73	1.13	1
Closed loop stability	Stable	Stable	Stable

5. CONCLUSION

The paper aims at modelling the system based on its available input output data and to compare performances of the designed controllers based on their time domain characteristics. Therefore, in this paper Ziegler nichols tuned PID controller, Smith predictor controller and Internal model controller are designed for controlling the temperature of a standard electrically heated oven. The standard Ziegler Nichols tuned PID controller along with PI controller based Smith predictor controller and internal model controller are practiced to control the system. The results are obtained using MATLAB SIMULINK environment. The results comparison suggests better performance and time domain characteristics of internal model controller over smith predictor controller followed by Ziegler Nichols tuned PID controller.

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