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Comparison of different controller strategies for Temperature control

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Abstract - *This paper projects a thorough comparative study of the development and validation of control analysis of a model based heat-exchanger system for different controllers such as feedback, feedback plus feed-forward and internal model controller to control the temperature of product in a system. For comparative analysis an example of Heat exchanger system is considered in this study. For analysis of system behavior a mathematical model is formulated and different control algorithms are developed with the help of sensory system. The temperature is delimited at the desired set point automatically. The performance of considered control strategies are assessed on the basis of transient response criterion (overshoot and settling time) and error-based criterion (Integral of absolute error and square error for set point). On the basis of performed studies for a second-order plus dead time system, it can be inferred that internal model control outperforms feedback PID and feedback plus feed-forward controller.*

Key Words: Heat Exchanger, PID, Temperature control, Feedback Controller, Feedforward Controller, Internal Model Controller.

1. INTRODUCTION

Pressure, level, temperature and flow are the main control parameters on which most of the process industries rely for controlling both set point and load variations. In a heat exchanger the main operation is transfer of heat which can be fluid to fluid or gas to gas [11]. The modeling and controlling the dynamics of heat exchanger is complex due to its non-linearity and poor dynamics. Finding a good control algorithm is one of the challenging tasks on which the design of heat exchange controller depends. To develop this controller a system designer needs an accurate mathematical model of the entire process (with all control parameters) and then should consider other aspects like process uncertainty, measurement noise and robustness of the system. A controller should perform in two operating regimes: The first one is servo control in which set-point tracking is the main concern and the other one is regulatory control where the focus is on load disturbance rejection and maintaining steady state conditions. So this study will focus on estimating the performance of some distinguished control algorithms to control the temperature of heat exchanger system.

What are the expectations from an industrial control system? It should have a fast response to transients like input variation and load variation. It should exhibit lowest possible error at steady state and lowest possible settling time for any disturbance induced. So If summarized the primary objective of a controller is low overshoot, minimum settling time and minimum steady state error. Processes like temperature control, valve control are individually single order control system which probably may or may not have a delay but a heat exchanger is derived by integration of these single order systems which makes it a second order system with a dead time. So the transfer function of a heat exchange system will be a second order plus dead time (SOPDT) function and it would need a second order PDT mathematical model to design its controller. However, there are approximations that will be used in this study to convert SOPDT model to a second order systems without dead time or delays. This will enable us to estimate the tuning parameters for the process controller.

Using a PID control configuration for a process controller has been very popular since its inception in the industrial and automation control. According to estimation, 98% systems controllers which are employed in this industry are PID controllers. The reason for their wide acceptance is: their simpler structure and implementation, low cost and ease in understanding the behavior of the individual control actions. However, using only PID controller as a control strategy in your process may not always cover the entire objective of controlling the system. A single PID controller can either provide better servo action or better regulation action. But in real-time problems, it is usually desired that the control strategy should provide both desired regulation. There are established tuning rules for first order and second order control systems but when we add delay to these systems then it changes order for it which makes it complex to tune. So for such cases best possible assumptions are to remove these delays and compensate them system time constant so as to make it standard second order process control model. This study revolves around comparing the industry best control algorithm for a heat exchange system. It will present 3 different types of controllers, all designed to achieve the control objectives declared at the beginning of this study. Firstly, would be a conventional PID controller, which is the most commonly chosen approach for a process control because of its simplistic nature [6]. After that a more advanced feedback control with a feed-forward controller is applied to understand the improvement over conventional PID i.e. comparison of desired robustness, system stability and how well they control the overshoot. The feed-forward controller when combined with a feedback controller worked better than conventional PID alone but still there was a scope of improvement visible. To further improve the control performance a most advanced industrial control method known as the internal method controller was implemented on the same system. IMC gained widespread acceptance because of single control variable of the entire system which is the closed loop time constant. Further to it, as you will go through the design you will find other added reason to use it.

This paper is organized as follows: Section 2 provides a preliminary idea about heat exchanger and individual process transfer functions. Section 3 presents different control algorithms and controllers modeling. Section 4 provides the problem formulation where the mathematical modeling of the heat exchanger is illustrated. It also shows simulation results of different controllers for set point regulation as well as disturbance rejection. Finally, the conclusion is provided in Section 5. In this study MATLAB Simulink platform is used to perform system level simulation and derive the tuning parameters in all control strategies.

2. HEAT EXCHANGER

In the process industries, heat is transmitted via radiation by mixing of hot and cold fluids or by conduction through the walls of a heat exchanger [10]. There are different types of heat exchanger used in industries which are categorized with respect to construction, transfer process, flow and phase. Shell and tube heat exchangers are the most versatile type of heat exchangers applicable for a wide range of operating temperatures and pressures [8, 9]. These types of heat exchanger make availability of relatively large ratio of heat transfer area to volume and weight. These are quite easy to construct in an inclusive collection of sizes and configurations. They are mechanically rugged enough to withstand normal shop fabrication stresses, shipping and field erection stresses, and normal operating conditions. It's periodic maintenance and cleaning is easy due to its simple structure which eases disassembly so that those components most subject to failure-gaskets and tubes can be easily replaced. They are widely used in the process industries, in conventional and nuclear power stations, refrigeration, power generation, heating, air conditioning, chemical processes, and medical applications.

A shell-and-tube heat exchanger is an extension of the double-pipe configuration (single pipe within a larger pipe). As its name indicates, this type of heat exchanger comprises of a large pressure vessel i.e. cylindrical shell with a bundle of tubes inside it. Colder fluid runs inside the tubes, and hotter fluid is allowed travel over the tubes (through shell) which will then transfer heat to the colder tubes eventually raising the temperature of colder fluid. The heat exchange tubes might be made up of several types of tubes: plain, longitudinally finned, etc. In this study, the heat exchanger considered is a fluid-fluid two pass countercurrent type and real time experimentation is performed for model identification of laboratory shell and tube type heat exchanger system. The sole purpose of using the heat exchanger is to control industrial fluid temperature coming out of this system.

2.1 System Description

Figure 1 shows a real time working block diagram of a heat exchanger system. The cold water is the input which supplies from the overheat tank to the shell side of the heat exchanger. Temperature sensor measures the temperature of output fluid. A 3-wire PT-100 RTD is used to measure the temperature as it can withstand high temperature while it maintains stability and is connected to the transmitter. The temperature transmitter drives the measurement signal to the controller. The RTD circuit produces a standard output of (4-20) mA which is proportional to the temperature. Then this output is read by the main controller using a data acquisition (DAQ) device (Analog to digital converter). The controller processes the error signal and decides the needed control action for temperature control. The controller unit sends the corresponding control signal to (current to pressure) a converter via another DAQ (Digital to analog converter) device converting it in range of (4-20) mA and output of the converter is a signal in (3-15) psi. The current to pressure converter is called as actuator which converts the output current of controller to appropriate pressure signal. The pressure signal is transmitted to control valve which acts as a final control element. The control valve triggers according to the control signal and allows the necessary steam to enter the heat exchanger for controlling the outlet temperature of heat exchanger.

The PID controller algorithm comes inside the main controller which takes the important processing of comparing the input received from sensor, comparing it with a reference temperature and then sending a signal to valve to take action to reach that desired temperature. A mathematical modeling of this system thus involves the transfer functions of all the individual processes to create the complete heat exchange system.

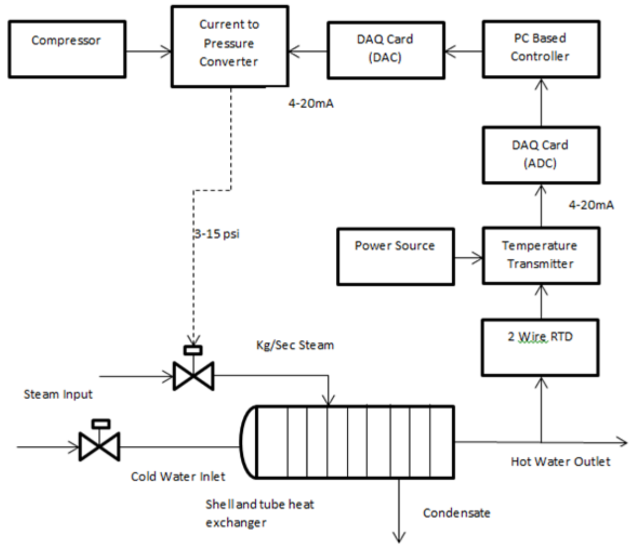

Figure -1: Block diagram of heat exchanger system

2.2 Mathematical Modeling

An actual heat exchanger was fabricated [1] according to the derived dimensions by carrying out the validation of this theoretical model based heat exchanger. After the setup on running practically in open loop configuration the derived results at 800 rpm of hot water pump and giving a step input of 50°C are as under depicted in Table I.

Time (sec)	Temperature(°c)
0.5	25.00
7.71	25.14
21.7	29.03
38.8	31.89
70.27	35.77
114.69	39.53
181.83	42.75
257.65	44.19
297.73	44.80
409.62	45.37
486.44	45.62
573.28	45.76
596.66	45.85
596.66	45.92

Table -1: Readings of Practical Performance in Open Loop: 800 rpm & 50°C

In the heat exchanger system, actuator, valve, sensor are mathematically modeled using the available experimental data [1].

2.2.1 Process Transfer Function

Considering temperature system as a first order system with time delay having transfer function, Gp [13]

$$G_P = \frac{\frac{N}{M} e^{-\tau_d s}}{(\tau s+1)} \quad (1)$$

N = Final value of Output;

M=final value of the step input;

M= 50 (Step input) - *from Table 1*;

N=46 (Response final value) - *from Table 1*;

Delay time = 0.5s

Time constant, $\tau = 63.2\%$ of Final

$$\tau = 63.2 \times \frac{46}{100}$$
$$\tau = 29.072$$
$$\tau \approx 29$$

$$G_P = \frac{\frac{46}{50} e^{-0.5s}}{(29s+1)}$$

$$G_P = \frac{0.92e^{-0.5s}}{(29s+1)}$$

2.2.2 Control Valve Transfer Function

Let's consider control valve T.F. and disturbances;

Data reference [1]

Maximum travel of control valve is given as =15 mm.

Time constant =3 sec

Pressure Range= (3-15) psi

Control valve gain $(K_v) = \frac{\text{Range of steam}}{\text{Pressure Range}}$

$$K_V = \frac{15}{(15-3)} = \frac{15}{12} = 1.25\text{psi/mA}$$

Transfer Function Control Valve (Actuator)

$$G_P = \frac{K_V}{(\tau_1 s+1)}$$

$$G_P = \frac{1.25}{3s+1} \quad (2)$$

2.2.3 Sensor Transfer Function

Considering Control Valve and Sensor T.F. with filter coefficient

Data reference [1]

Time constant =1-2 sec (considering 1 sec)

Range= $(0-100)°C$

Sensor gain $K_s = \frac{(20-4)mA}{(100-0)°C} = \frac{16}{100} = 0.16$

Transfer Function of sensor

$$H(s) = \frac{K_s}{(\tau_2 s+1)} \quad (5)$$

$$H(s) = \frac{0.16}{(s+1)} \quad (6)$$

2.2.4 Disturbance Transfer Function

Data reference [1]

Disturbance Gain=1

Time Constant = 3 sec

Transfer Function of Disturbance

$$G_d(s) = \frac{K_d}{(\tau_1 s+1)} \quad (7)$$

$$G_d(s) = \frac{1}{(3s+1)} \quad (8)$$

3. HEAT EXCHANGE CONTROL METHODS

The heat-exchanger is supported by feedback and override control system to control, modify and regulate the temperature of water. PID Controller, Feed-Forward Controller and IMC Controller are three most prevalent and used methods for control.

3.1. PID Controller

This controller is ordinarily established by combining three terms viz., proportional term differential term and integral term together in a linear form. The proportional term reduces error due to disturbance, integral term eradicates steady-state error and the derivative term dampens the dynamic response, and hence improving the system stability. This controller is easy for development and implementation which also makes it available for widely used in solving process control problems.

Figure 2 shows the functional block diagram of PID controller based control system where a PID controller mathematical model represented as follows;

$$g_c(s) = K_c\left[1 + \frac{1}{\tau_i s} + \tau_d s\right] \quad (9)$$

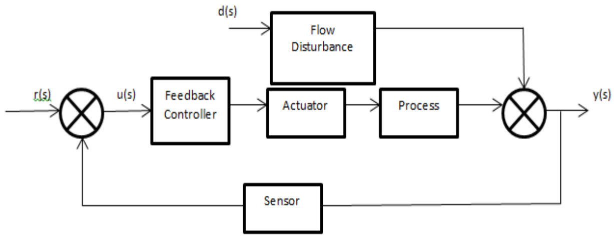

Figure -2: Block Diagrams of PID control system

PID controllers are tuned with various tuning methods like Zn-Ns, Cohen-coon [7], GM-PM, IMC etc. However, the internal model control (IMC) tuning gives the best results for PID parameters. So the paper uses IMC tuning parameters.

3.1.1. Internal Model control (IMC) Based PID controller

The heat exchanger process control transfer function $g_P(s)$ is given by:

$$g_P(s) = \frac{K_P e^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)} \quad (10)$$

Step-1 Use Pade approximation to accommodate delay compensation

It can be approximated with zero order 'Pade 'approximation [2]

$$g_P(s) = \frac{K_P}{[(\tau_1+0.5\theta)s+1][(\tau_2+0.5\theta)s+1]} \quad (11)$$

Considering,

$$(\tau_1 + 0.5\theta) = \alpha$$

$$(\tau_2 + 0.5\theta) = \beta$$

Generating the second order delay equation to second order without delay

$$g_P(s) = \frac{K_P e^{-\theta s}}{(\alpha s+1)(\beta s+1)} \quad (12)$$

Step-2 Form the idealized controller

$$\tilde{q}(s) = g^{-1}{}_P(s) \quad (13)$$

$$\tilde{q}(s) = \frac{(\alpha s+1)(\beta s+1)}{K_P} \quad (14)$$

Step-3 Add the filter

$$q(s) = \tilde{q}(s) \cdot f(s) \quad (15)$$

$$q(s) = \frac{(\alpha s+1)(\beta s+1)}{K_P} \cdot \frac{1}{(\lambda s+1)} \tag{16}$$

Step-4 Find the PID equivalent for IMC tuning

$$g_c(s) = \frac{q(s)}{1-g_P(s)\cdot q(s)} \tag{17}$$

$$g_c(s) = \frac{\tilde{q}(s)\cdot f(s)}{1-g_P(s)\cdot q(s)} \tag{18}$$

$$g_c(s) = \frac{\frac{(\alpha s+1)(\beta s+1)}{K_P}\cdot\frac{1}{(\lambda s+1)}}{1-\frac{K_P}{(\alpha s+1)(\beta s+1)}\cdot\frac{(\alpha s+1)(\beta s+1)}{K_P}\cdot\frac{1}{(\lambda s+1)}}$$

$$g_c(s) = \frac{\frac{(\alpha s+1)(\beta s+1)}{K_P}\cdot\frac{1}{(\lambda s+1)}}{1-\frac{1}{(\lambda s+1)}}$$

$$g_c(s) = \frac{1}{K_P\cdot\lambda s}[(\alpha s + 1)(\beta s + 1)]$$

$$g_c(s) = \frac{\alpha\beta s^2+(\alpha+\beta)s+1}{K_P\cdot\lambda s}$$

$$g_c(s) = \left(\frac{\alpha+\beta}{\lambda K_P}\right)\cdot\left[\frac{\alpha\beta s^2+(\alpha+\beta)s+1}{(\alpha+\beta)s}\right] \tag{19}$$

Comparing with IMC based controller transfer function, $g_c(s)$, where

$$g_c(s) = K_c\cdot\left[\frac{\tau_i\tau_d s^2+\tau_i s+1}{\tau_i s}\right] \tag{20}$$

Henceforth, IMC –PID tuning parameters derived here are

$$K_c = \left(\frac{\alpha+\beta}{\lambda K_P}\right) \tag{21}$$

$$K_c = \frac{(\tau_1+0.5\theta)+(\tau_2+0.5\theta)}{K_P\cdot\lambda}$$

$$K_c = \frac{(\tau_1+\tau_2+\theta)}{K_P\cdot\lambda} \tag{22}$$

$$\tau_i = (\alpha + \beta) \tag{23}$$

$$\tau_i = (\tau_1 + 0.5\theta) + (\tau_2 + 0.5\theta)$$

$$\tau_i = (\tau_1 + \tau_2 + \theta) \tag{24}$$

$$\tau_d = \left(\frac{\alpha\cdot\beta}{\alpha+\beta}\right) \tag{25}$$

$$\tau_d = \left|\frac{(\tau_1+0.5\theta)(\tau_2+0.5\theta)}{(\tau_1+\tau_2+\theta)}\right| \tag{26}$$

This is the IMC tuning for which will use to determine the parameters of the feedback/PID controller. For this work

$$\tau_1 = 3 \text{ sec}$$

$$\tau_2 = 29 \text{ sec}$$

$$\lambda = 1$$

$$\theta = 0.5$$

$$K_p = 1.25 \times 0.92 = 1.15$$

The parameters of PID controller can determine by using this data in the equations (22), (24) and (26),

$$K_c = \frac{3 + 29 + 0.5}{1.15 \times 1}$$

$$K_c = 28.26$$

$$\tau_i = 3 + 29 + 0.5 = 32.5$$

$$K_i = \frac{1}{\tau_i} = \frac{1}{32.5}$$

$$K_i = 0.0307$$

$$\tau_d = \frac{(3+0.5\times0.5)(29+0.5\times0.5)}{(3+29+0.5)}$$

$$\tau_d = \frac{3.25\times29.25}{32.5}$$

$$K_d = \tau_d = 2.925$$

Finding few more tuning points of PID in similar way for different values of filter time constant, λ .

$\lambda = 0.5$ $K_c = 56.52,\ K_i = 0.0307, K_d = 2.925$

$\lambda = 1.0$ $K_c = 28.26,\ K_i = 0.0307, K_d = 2.925$

$\lambda = 2.0$ $K_c = 14.13,\ K_i = 0.0307, K_d = 2.925$

$\lambda = 3.0$ $K_c = 09.42,\ K_i = 0.0307, K_d = 2.925$

3.1.2. Feed-Forward Controller

A feed forward algorithm eliminates the intrinsic limitation of feedback control scheme i.e. in the feedback system the controller acts after the disturbance distorts the required control objective but a feed forward controller estimates the error and changes the manipulating variable before the disturbance can affect the output. A feedback control cannot attain the desired steady state if frequent disturbances occur. To minimize the overshoot and get steady state, feed-forward control is used which limits the deviation caused by the disturbance which is necessary to estimate for proper working of Feed-forward control. Feed-forward control cannot work alone, so it works alongside feedback control. A feed-forward controller is used with the feedback (PID) controller introduced in the forward path of the process. It is expected that the combined effect of both feedback and feed forward controller improves the control strategy over standalone feedback control.

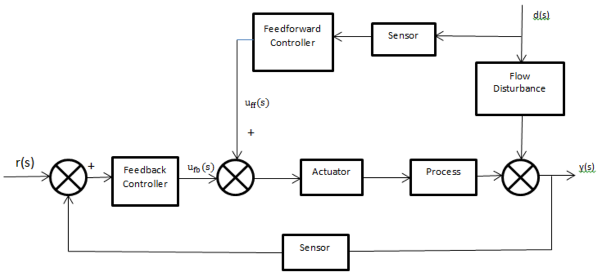

Figure-3: Block Diagrams of FEED FORWARD control system

In feed forward controller we provide the flow disturbance as the input fluid. Figure 3 shows the block diagram Feed forward control along with the feedback control.

The flow disturbance is measured or estimated and the feed-forward controller tries to compensate the disturbance effect on the system. The processed signal from Feed forward controller and feedback controller are summed up and provided to the process.

The transfer function of feed-forward controller can be represented as

$$G_{cf}(s) = -\frac{G_d(s)}{G_P(s)} \quad (27)$$

Here, $G_{cf}(s)$ = Transfer Function of feed-forward controller

$G_P(s)$ = Transfer Function of process

$G_d(s)$ = Transfer Function of flow disturbance

Feeding the values of entire process, we get;

$$G_d(s) = \frac{1}{3s+1} \quad (28)$$

$$G_P(s) = \frac{1.25}{(3s+1)} \cdot \frac{0.92}{(29s+1)} \quad (29)$$

$$G_P(s) = \frac{1.15}{(87s^2+32s+1)}$$

$$G_{cf}(s) = \frac{-\frac{1}{(3s+1)}}{\frac{1.15}{(87s^2+32s+1)}} \times \frac{1}{(\lambda s+1)}$$

Looking at the above equation it is clear that filter time constant, λ, is the only tuning parameter for this feed forward transfer function.

$$G_{cf}(s) = \frac{(-87s^2-32s-1)}{1.15(3s+1)(\lambda s+1)}$$

$$G_{cf}(s) = \frac{(-87s^2-32s-1)}{(3.45\lambda s^2+1.15(3+\lambda)s+1.15)} \quad (30)$$

Now, this feed forward controller $G_{cf}(s)$ transfer function will be used in simulation model in the forward path of the process along with other system transfer functions and feedback controller $g_c(s)$ with same P,I,D parameters but will be tuned with different filter time constant along with Feed forward controller. This is described in FEED FORWARD simulation section 4.

3.1.3. Internal Model controller (without PID)

In the field of chemical engineering IMC (internal model control) is one of the most popular techniques which offers a translucent frame for control system design and tuning[4].The basic aim of introducing IMC is to limit the effects of error and disturbance caused by model mismatch. The process model derived can be a forward model or inverse model. The controller is carved out from the inverse model whereas the forward model is placed in parallel with the actual process. That is standard modeling method for IMC control strategy. The structure of internal model controller is shown in figure 4. Filter time constant, λ is introduced in the system to achieve good disturbance rejection.

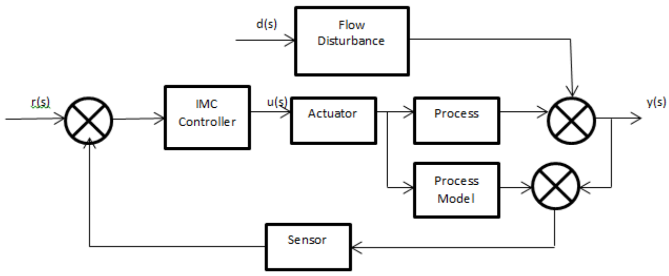

Figure -4: Block Diagrams of IMC control system

The transfer function of the process is shown in eq.

$$G_P(s) = \frac{K_P e^{-\theta s}}{(\tau_1 s+1)(\tau_2 s+1)} \quad (31)$$

Step-1 Use a second-order Pade approximation for dead time

$$e^{-\theta s} = \frac{(0.0207s^2-0.25s+1)}{(0.0207s^2+0.25s+1)} \quad (32)$$

Where $\theta = 0.5$

$$\widehat{G_P}(s) = \frac{K_P}{(\tau_1 s+1)(\tau_2 s+1)} \cdot \frac{(-0.0207s^2-0.25s+1)}{(0.0207s^2+0.25s+1)} \quad (33)$$

Step-2 Factor out the non-invertible elements

$$\widehat{G_P}(s) = \hat{G}_{P-}(s) \cdot \hat{G}_{P+}(s) \quad (34)$$

$$\hat{G}_{P-}(s) = \frac{K_P}{(\tau_1 s+1)(\tau_2 s+1)(0.0207s^2+0.25s+1)} \quad (35)$$

$$\hat{G}_{P+}(s) = (0.0207s^2 - 0.25s + 1) \quad (36)$$

Step-3 Add the filter

$$Q(s) = \widehat{G^{-1}{}_P}(s) \cdot f(s) \quad (37)$$

$$f(s) = \frac{1}{\lambda s+1} \quad (38)$$

$$G^{-1}{}_P(s) = \frac{(\tau_1 s+1)(\tau_2 s+1)(0.0207s^2+0.25s+1)}{K_P} \quad (39)$$

$$Q(s) = \frac{(\tau_1 s+1)(\tau_2 s+1)(0.0207s^2+0.25s+1)}{K_P(\lambda s+1)^4} \quad (40)$$

From the above equation, the only tuning parameter is λ and hence IMC controller is simple.

Step-4 Find the Transfer Function of IMC controller

$$Q(s) = \frac{(29s+1)(3s+1)(0.0207s^2+0.25s+1)}{1.15(\lambda s+1)^4}$$

$$Q(s) = \frac{(87s^2+32s+1)(0.0207s^2+0.25s+1)}{1.15(\lambda s+1)^4}$$

$$Q(s) = \frac{1}{1.15}\left[\frac{1.801s^4+22.41s^3+95.02s^2+32.25s+1}{\lambda^4 s^4+4\lambda^3 s^3+6\lambda^2 s^2+4\lambda s+1}\right] \quad (41)$$

IMC Method does not have any P, I, D tuning parameters; it only needs filter time constant λ to be tuned with best possible outputs.

4. SIMULATION

In this work different controllers are used to control the temperature of a shell and tube heat exchanger system. This section discussed the simulated study of the controller performance which is one of the widely researched areas which determine the performance of the controller by various methods.

4.1. Parameters for Performance Evaluation

This study has considered combination of 3 performance parameters of the step response which can provide a better indication of the efficiency of the control algorithms. The considered parameters are maximum overshoot, settling time, IAE and ISE.

4.1.1. Maximum Overshoot

Peak overshoot is defined as the deviation of the response at peak time from the final value of response or desired value. It is the normalized difference between the peak of the time response and steady output. It is also called the **Peak overshoot.**

$$\text{Max Percentage Overshoot} = \frac{C(t_p)-C(\infty)}{C(\infty)} \times 100 \quad (42)$$

4.1.2. Settling Time

It is the time required for the response to reach the steady state and stay within a specified tolerance band of its final value. The tolerance band is taken generally as 2-5%.

4.1.3. Integral of the Absolute Error (IAE)

In closed loop system the error signal is the difference between input signal and the feedback signal. IAE integrates the absolute error over time [5]. It doesn't add weight to any of the errors in a systems response. It tends to produce slower response than ISE optimal systems, but usually with less sustained oscillation.

$$IAE = \int_{t_o}^{t_f} |e(t)|dt \quad (43)$$

4.1.4. Integral of the Square Error (ISE)

ISE integrates the square of the error over time [5]. ISE will penalize large errors more than smaller ones (since the square of a large error will be much bigger).Control systems specified to minimize ISE will tend to eliminate large errors quickly, but will tolerate small errors persisting for a long period of time. Often this leads to fast responses, but with considerable, low amplitude, oscillation.

$$ISE = \int_{t_o}^{t_f} e^2(t)dt \quad (44)$$

Where, e(t) is the error of system, t_o is the time at which set point or disturbance is applied. In this work the set-point and disturbance both are applied at *t* = 0 s.

4.2. Simulation study

In this study of temperature control of a shell and tube heat exchanger system is analyzed for the different control mechanism i.e. PID, feed-forward and IMC controllers respectively and the simulated study of the controller performance is discussed in this section. The simulations are carried out using MATLAB (version R2018) software, for set point tracking and load regulation. The transient response i.e. peak overshoot and settling time for unit step response of and the error responses of feedback, feedback plus feed-forward and internal model controllers are summarized in Table 5.

λ	Overshoot	Settling time	IAE	ISE
0.2	101.71	21.01 sec	0.728	0.060
0.5	45.92	10.01 sec	0.595	0.049
1	17.30	32.89 sec	0.721	0.052
2	27.20	20.35 sec	0.853	0.055
3	13.24	42.10 sec	0.925	0.057

Table-2: Response of Feedback PID controller for different values of λ

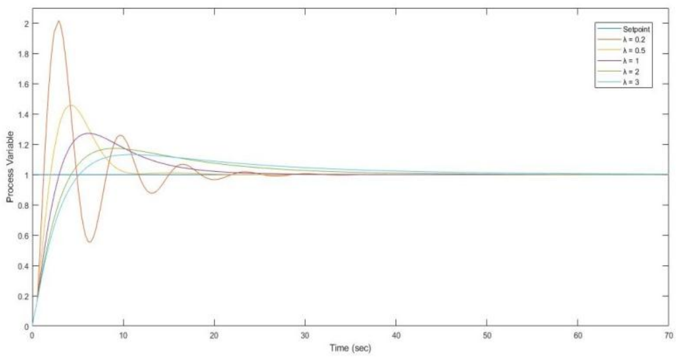

Figure – 6: Process Variable variation in Feedback PID controller

λ	Overshoot	Settling time	IAE	ISE
0.2	83.50	18.70 sec	0.623	0.052
0.5	33.35	11.35 sec	0.559	0.046
1	15.91	20.30 sec	0.626	0.048
2	5.81	25.17 sec	0.626	0.051
3	1.42	7.23 sec	0.561	0.054

Table-3: Response of Feedback Feed-forward controller for different values of λ

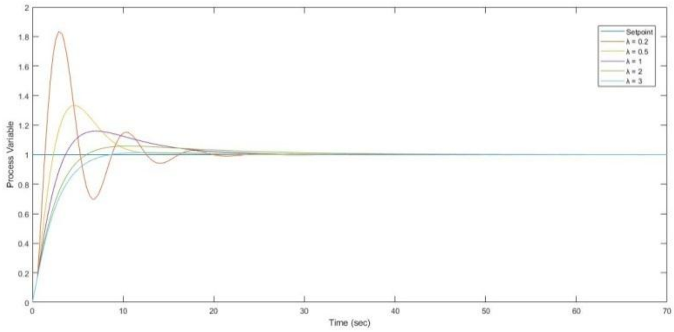

Figure-7: Process Variable variation in Feed-forward controller

λ	Overshoot	Settling time	IAE	ISE
0.2	0.013	11.50 sec	0.799	0.088
0.3	0.015	11.28 sec	0.799	0.088
0.5	0.010	10.59 sec	0.799	0.088
1	0.546	7.62 sec	0.803	0.086
2	3.651	17.80 sec	0.800	0.087
3	3.946	22.92 sec	0.800	0.086

Table-4: Response of IMC controller for different values of λ

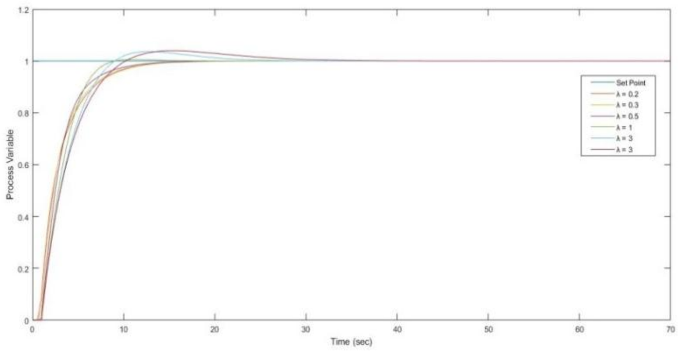

Figure - 8: Process Variable variation in IMC controller

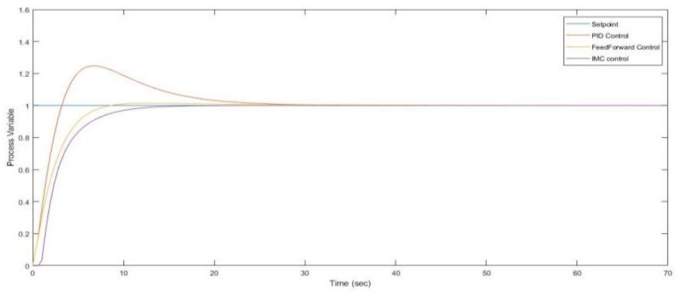

Figure-9: Process Variable variation in different control systems

Controller	Overshoot	Settling time	IAE	ISE
Feedback PID (λ = 1)	17.30 %	32.89 sec	0.74	0.05
Feed-forward (λ = 3)	1.42 %	7.23 sec	0.56	0.05
IMC (λ = 1)	0.51 %	7.64 sec	0.80	0.08

Table-5: Results for Transient response and Error indices of different control strategies

Looking over the simulation results, it is evident that at the best tuned filter time constant value, the overshoot and setting time is decreased significantly. The filter time constant is significance of filter cut-off frequency and delay it introduces in the system. Because time constant decreasing means higher frequency cut-off is being used, which is one of the reasons why lower time constants value have lower overshoot values.

Looking at table 5 it can be concluded that even with best filter time constant the PID and Feed-forward control systems are not that good as IMC Control. Comparing IMC with PID and Feed-forward methods, it is visible that by choosing right filter time constant or filter frequency the IMC comes out to be best control strategy than other controllers.

In PID controller we set the parameters by using IMC tuning method to get satisfactory response. For a unit step set point we found overshoot and large settling time both of which are undesirable. The feedback PID controller shows 17.30 % of overshoot and 32.89 sec of settling time. Then feed-forward controller is added with feedback controller to avoid high overshoot of classical PID controller. The arrangement of feedback plus feed-forward controller reduces the overshoot to 1.42 % and settling time to 7.23 sec. After that model based control (IMC) is used to minimize the overshoot further which displays an overshoot of 0.51% with the 7.64 sec settling time.

5. CONCLUSION

This paper presented a thorough comparative study between different control algorithms to control the outlet temperature of a shell and tube heat exchanger system. This work strives to find a best suitable method for the heat exchanger system which can give most satisfactory performance parameters of a system, i.e., tracking performance, disturbance rejection, and robustness. To achieve and analyze this, three different controllers have been tried out using some widely accepted tuning rules for simple conventional control structures.

Firstly, we have developed a mathematical process model of the heat exchanger through experimental data [1] and then cultivated the respective controller by using this process model along with the experimental data. The assessment of different controllers has been evaluated on the basis of transient characteristics and error indices. From the simulation results, it is found that IMC controller outperformed the feedback and feedback plus feed-forward controller. IMC gives good and reasonable result for both tracking performance as well as disturbance rejection. The feedback and feed-forward controllers display a higher degree of overshoot and settling time while the internal model control negates the overshoot and takes adaptable settling time.

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