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# Comparison of Controller Tuning Techniques for A Temperature Control of STHX Process

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***Abstract***—This paper presents the comparison of three controller tuning techniques for a Temperature Control process. The controller tuning techniques include Zeigler-Nichols (Z-N), Wang-Juang-Chan (W-J-C) and Internal Model Control based Proportional-Integral-Derivative (IMC-PID) controller. The FOPDT model for the Shell and Tube Heat Exchanger (STHX) is first obtained by first principles. The first principles model is developed using the energy balance equation of the STHX system. Then the above said tuning techniques are applied to the STHX system. The purpose of these tuning techniques is to regulate the hot water outlet temperature to a desired value by manipulating the cold water flow rate. Finally, the performances of the tuning techniques are validated with the help of performance error indices such as ISE, IAE, ITAE, and ITSE.

***Keywords—*** STHX, FOPDT, Z-N, W-J-C, IMC-PID, ISE, IAE, ITAE, ITSE.

## I. INTRODUCTION

Proportional Integral Derivative (PID) controllers are the most commonly used controller in process industries because of their robustness, simplicity and their effective practical application. Various tuning methods have been proposed for PID controllers. In this paper ZN-PID, WJC-PID and IMC-PID tuning techniques are analyzed with the help of Shell and Tube Heat Exchanger (STHX) system. Heat Exchanger transfers heat from one medium to the other medium without any direct contact with each other.

This paper is organized as: Section II contains the related work of various tuning techniques; Section III describes the piping and instrumentation diagram of STHX process. Section IV and Section V gives the description of mathematical modeling and modeling of the process. Section VI explains the three controller tuning techniques, Section VII describes results and discussions and Section VIII concludes this work with future scope.

## II. RELATED WORK

A comparison of tuning methods such as IMC-PID and Z-N based PID in frequency domain has been applied to an empirical model of a counter flow, STHX system. Counter flow arrangement means hot fluid pass from one end and the cold fluid from the other end. From the results, IMC based PID shows better performances than extension of Z-N based PID in frequency domain [1].

Tuning the controller is done by adjusting the filter time constant which provides robustness and improved performance of the closed loop system. To evaluate the performance of IMC-PID, the superheated steam temperature system of 500 MW boiler is considered in the case study. The results indicate that IMC-PID provides better performance and robustness compared to Cohen–Coon open loop and C-H-R tuning techniques [2]. The performance of the temperature process with Ziegler-Nichols (Z-N) PID, Cohen-Coon (C-C) PID, Modified Z-N PID with overshoot and without Overshoot, Tyreus-Luyben (T-L) PID, Chien, Hrones and Reswick (C-H-R) PID with Set point tracking and with Load Rejection, IMC-PID and Model Predictive Controller are analysed with its time domain specifications in terms of peak overshoot, rise time, settling time, peak time, and performance measures (ISE, ITAE, IAE, MSE) in [3].

To control the liquid level of conical tank system PID controller tuning is predominantly used in several industries. Z-N, Modified Z-N, IMC, T-L and C-H-R are the tuning methods used to attain high stability [4]. PID controller has been tuned with the help of Z-N and Relay Auto-tuning (RA) methods. The comparative study was attained in terms of many performance specifications such as rise time, settling time etc., and various performance error indices [5]. The mathematical modeling and the transfer function model of the STHX system for different operating regions are tuned with the help of ZN-PID tuning method in [6].

Article [7] utilizes a differential equation model for the STHX process. Here an effort is made to control the STHX process with multiple model approach using Z-N tuning technique. The step response of a heat exchanger model using various techniques viz. Z-N PID (Method II), C-C Method, T-L and Approximated M-constrained Integral Gain Optimization method are compared in [8]. Finally T-L method has settling time which is not very large and also gives tolerable overshoot comparatively. PI controller tuning methods (Skogestad, Z-N, Hagglund and Astrom, T-L and Relay method) are used to tune a temperature controller for an air heater [9]. The performance indices based on set point tracking, disturbance compensation and stability margin are calculated.

Two conventional tuning methods such as relay auto tuning and IMC-based PID tuning methods are used to design controller for the heat exchanger system. The controllers are subjected experimentally to both servo and regulatory changes [10]. From the experimental results, IMC based controller shows better results comparatively in terms ISE and ITAE. Step response of Z-N PID (Method II), C-C and Fuzzy Logic Controller was compared for a heat exchanger model and their responses were obtained [11]. Comparison of various tuning methods is studied for SISO systems in [12]. These tuning methods are implemented for first, second and third order systems with dead time. The C-H-R and W-J-C (Wang-Juang-Chan) tuning techniques are good for tracking control whereas in the case of disturbance rejection C-C or Z-N techniques provide better performance measures [13].

This paper is organized in a way over the ideas gained from various tuning techniques through the literature. Modeling the STHX process is obtained using first principles and the three tuning techniques (Z-N, W-J-C and IMC-PID) for regulating the hot water outlet temperature is explained in the forthcoming sections of this script.

## III. Piping and Instrumentation Diagram of STHX Process

The shell and tube heat exchanger consists of 37 copper tubes and the length of the tubes is of 750 mm with a single pass arrangement. The hot and cold water can be arranged in co-current and counter-current manner. Water is heated to a specific operating temperature in the process tank. The disturbance tank is used to study for disturbance rejection.

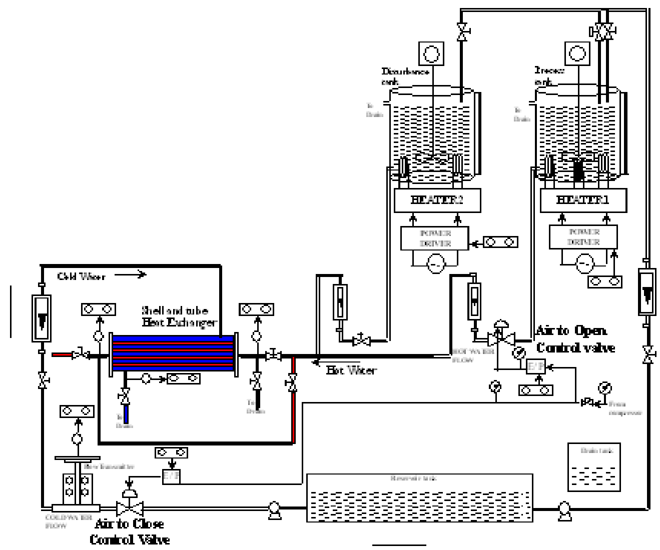


*Figure 1.*P & ID of STHX

The hot water runs from the process tank and passes through the tube side of the heat exchanger. Cold water is supplied at room temperature and runs from the reservoir tank into the shell side of the heat exchanger. The two power drivers regulate the voltage and current to the heaters, which in turn regulates the temperature of the water in the process and disturbance tank. The inlet and outlet temperatures of the hot and cold water are measured using the Resistance Temperature Detectors. The cold water flow rates are measured using Differential Pressure Transmitter. The cold and hot water inlet flow of the shell side and tube side fluids are manipulated using pneumatic control valves. The controlled variable is hot water outlet temperature whereas the manipulated variable considered here is the cold water flow rate. The process parameters are obtained from the first principles model which is simulated using MATLAB/Simulink.

## IV. Mathematical Modeling

### *A. Energy Balance Equations for STHX system*

The STHX consists of two sections namely the shell and tubes. For designing the mathematical model of STHX, the following was assumed. The two sections are separated into small control volumes. These control volumes were assumed to have a constant temperature over that particular volume. Since the STHX is insulated, there is no heat loss from the heat exchanger to the surrounding. Rate of energy stored in the control volume is equal to the rate of gain of energy from the neighbouring control volume. To observe the model of the method, hot water tubes are kept at a particular temperature. On that point a little step change in cold water inflow rate is set, both in positive and negative ways to acquire separate response curves.

 

The Energy Balance Equations for shell-side and tube-side respectively are given below. The parameter specifications at the nominal operating point are listed in table 1.

- *Shell side Equation*

$$\frac{\rho_s C_s V_s}{N} * \frac{dT_{co}}{dt} = \dot{m}_s C_s (T_{ci} - T_{co}) + \frac{h_s A_s}{N}(T_{ho} - T_{co}) \quad (1)$$

- *Tube Side Equation*

$$\frac{\rho_t C_t V_t}{N} * \frac{dT_{ho}}{dt} = \dot{m}_t C_t (T_{hi} - T_{ho}) + \frac{h_t A_t}{N}(T_{co} - T_{ho}) \quad (2)$$

*B. Parameter Specifications*

Table 1.Catalogue data of STHX

| Inputs | Value | Units |
|---|---|---|
| Density of Water ($\rho_s, \rho_t$) | 1000 | Kg/$m^3$ |
| Specific Heat Capacity of water ($C_s, C_t$) | 4230 | J/Kg °C |
| Shell Heat Transfer Area ($A_s$) | 0.281 | $m^2$ |
| Tube Heat Transfer Area ($A_t$) | 0.253 | $m^2$ |
| Shell side volume ($V_s$) | 2.62*10^-4 | $m^3$ |
| Tube side volume ($V_t$) | 1.43*10^-4 | $m^3$ |
| Heat transfer coefficient of shell ($h_s$) | 2162 | W/$m^2$°C |
| Heat transfer coefficient of tube ($h_t$) | 2162 | W/$m^2$°C |
| Mass flow rate of cold water ($\dot{m}_s$) | 0-0.12 | Kg/S |
| Mass flow rate of hot water ($\dot{m}_t$) | 0.0282 | Kg/S |
| Cold water inlet temperature ($T_{ci}$) | 33 | °C |
| Hot water inlet temperature ($T_{hi}$) | 55 | °C |
| Number of control volume (N) | 10 | NA |

## V. MODELING

*A. Positive and Negative Step Change in input*

Based on the Energy Balance Equations and Parameter Specifications a model using Matlab/Simulink has been created for which the inputs given are positive and negative step change in input. An increase of step change in flow rate in terms of 0.02 lps was specified till the nominal flow rate is reached and based on these values the response was acquired. A decrease of step change in flow rate from the nominal value was set till it reaches 0.02 lps and the necessary plot was attained. From this open loop response, the open loop parameters have been calculated.

*B. Process Parameters*

The open-loop parameters alike Process Gain Kp, Time Constant τ and Time Delay θ are acquired from the response curves, which are computed and displayed in the table 2.

Table 2.Open-loop Parameters

| **Flow Rate (lps)** | **Operating Region (°C)** | **Gain °C/lps** | **Time Constant (Sec)** | **Dead Time (Sec)** |
|---|---|---|---|---|
| 0.02-0.04 | 44.96-45.63 | -33.3 | 0.827 | 0.137 |
| 0.04-0.06 | 44.65-44.96 | -15.5 | 0.773 | 0.134 |
| 0.06-0.08 | 44.52-44.65 | -6.5 | 0.558 | 0.245 |
| 0.08-0.10 | 44.41-44.52 | -5.5 | 0.606 | 0.122 |
| 0.10-0.12 | 44.34-44.41 | -3.5 | 0.693 | 0.163 |
| 0.12-0.10 | 44.42-44.35 | -3.5 | 0.335 | 0.161 |
| 0.10-0.08 | 44.53-44.42 | -5.5 | 0.702 | 0.094 |
| 0.08-0.06 | 44.68-44.53 | -7.5 | 0.776 | 0.159 |
| 0.06-0.04 | 44.96-44.68 | -14 | 0.816 | 0.192 |
| 0.04-0.02 | 45.63-44.96 | -33.5 | 1.17 | 0.22 |

## VI. CONTROLLER TUNING TECHNIQUES

Zeigler-Nichols tuning, Wang-Juang-Chan tuning and IMC-PID are the three types of tuning used for comparative study in this paper.

The process model is given by

$$H(s) = \frac{K}{\tau s + 1} e^{-\theta s} \quad (3)$$

*A. Zeigler-Nichols Tuning*

Z-N method based on sustained oscillations was first proposed by Ziegler and Nichols in 1942. This method is possibly the most known and widely used method for tuning of PID controllers. It is also known as continuous cycling or ultimate gain tuning method. The tuning parameters [7] are given by

$$K_c = \frac{1.2\tau}{\theta * K} \quad (4)$$

$$\tau_i = 2 * \theta \quad (5)$$

$$\tau_d = 0.5 * \theta \quad (6)$$

*B. Wang-Juang-Chan Tuning*

This tuning rule was proposed by Wang, Juang, and Chan based on the optimum ITAE criterion. It is a simple and effective method for choosing the PID parameters. If the parameters K, τ and θ of the plant model are known, then the controller settings [14] are given by

$$K = \frac{\left(0.7303 + 0.5307\ {}^{\tau}/_{\theta}\right)(\tau + 0.5\,\theta)}{K\,(\tau + \theta)} \quad (7)$$

$$\tau_i = \tau + 0.5\,\theta \quad (8)$$

$$\tau_d = \frac{0.5\,\theta\,\tau}{\tau + 0.5\,\theta} \quad (9)$$

*C. IMC-PID Tuning*

This advanced controller concept gives perfect control and stable results. IMC tuning method is efficient in controlling the overshoot and the dynamics of temperature process. The IMC has a single tuning parameter ($\lambda$) to adjust the performances and robustness of the controller. The controller settings [15] are given by

$$K = \frac{2\tau + \theta}{K(2\lambda + \theta)} \quad (10)$$

$$\tau_i = \tau + \frac{\theta}{2} \quad (11)$$

$$\tau_d = \frac{\theta\tau}{2\tau + \theta} \quad (12)$$

## VII. Results and Discussion

The closed-loop parameters are calculated using the open-loop parameters by three tuning techniques namely the Zeigler-Nichols, Wang-Juang-Chan and IMC-PID tuning techniques. The PID Controller parameters for two operating regions are shown in the table 3 and table 4. The controller tuning performances has been validated based on set point tracking and disturbance rejection. Figure 3 and figure 4 shows the comparison plots of the three tuning techniques subjected to servo and regulatory changes. Z-N has higher overshoot, W-J-C has minimal overshoot and IMC-PID has no overshoot. For time domain specifications, IMC-PID has better responses comparatively. Table 5 and table 6 shows various performance error indices. The performance error indices include Integral Square Error (ISE), Integral Absolute Error (IAE), Integral Time Absolute Error (ITAE) and Integral Time Square Error (ITSE). W-J-C performs well with performance error indices for positive step change but with negative step change IMC-PID has better responses comparatively.

Table 3.Region 1

Flow Rate (0.04-0.06) and Operating Regions (44.65-44.96)

| Parameters | Z-N | W-J-C | IMC-PID |
|---|---|---|---|
| **Kc** | -0.447 | -0.2266 | -0.087834 |
| **Ki** | -1.668 | -0.2698 | -0.1046 |
| **Kd** | -0.0299 | -0.01397 | -0.005446 |

Table 4.Region 2

Flow Rate (0.08-0.06) and Operating Regions (44.68-44.53)

| Parameters | Z-N | W-J-C | IMC-PID |
|---|---|---|---|
| **Kc** | -0.781 | -0.4051 | -0.4970 |
| **Ki** | -2.456 | -0.4735 | -0.58097 |
| **Kd** | -0.0621 | -0.02922 | -0.0358 |

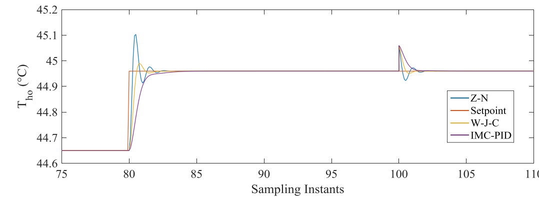


Figure 2.For Operating Region 44.65- 44.96 with Servo response at 80th Sampling Instants and Regulatory response at 100th Sampling Instants.

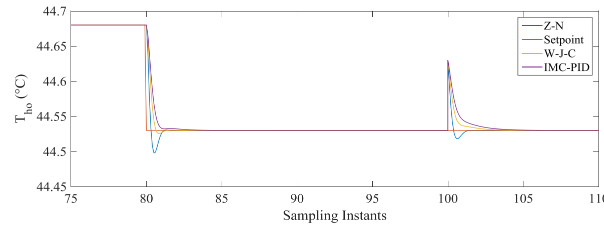


*Figure 3*.For Operating Region 44.68- 44.53 with Servo response at 80th Sampling Instants and Regulatory response at 100th Sampling Instants.

Table 5.Region 1

Flow Rate (0.04-0.06) and Operating Regions (44.65-44.96)

| Parameters | Z-N | W-J-C | IMC-PID |
|---|---|---|---|
| ISE | 0.02253 | 0.02033 | 0.03631 |
| IAE | 0.1197 | 0.09446 | 0.1912 |
| ITAE | 0.2865 | 0.2184 | 0.4785 |
| ITSE | 0.04873 | 0.04308 | 0.08217 |

Table 6.Region 2

Flow Rate (0.08-0.06) and Operating Regions (44.68-44.53)

| Parameters | Z-N | W-J-C | IMC-PID |
|---|---|---|---|
| ISE | 0.006042 | 0.005584 | 0.005161 |
| IAE | 0.06605 | 0.05202 | 0.04611 |
| ITAE | 0.1617 | 0.1214 | 0.1066 |
| ITSE | 0.01336 | 0.01193 | 0.01096 |

## VIII. Conclusion and Future Scope

The FOPDT model is obtained from the energy balance equation of the STHX system. The controller tuning techniques such as Zeigler-Nichols (Z-N), Wang-Juang-Chan (W-J-C) and Internal Model Control (IMC) based Proportional-Integral-Derivative (PID) controller are applied to the STHX system from which the performances of the tuning techniques are analysed. The performance error indices indicate that W-J-C has minimal IAE, ISE, ITAE and ITSE for positive step change and IMC-PID has minimal error indices for negative step change. Based on time domain specifications, it is clear that IMC-PID has lesser settling time with no overshoot and W-J-C has minimal overshoot with lesser settling time whereas, Z-N has maximum overshoot and settling time. As a future work, some advanced intelligent controller strategies could be designed.

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