PID Temperature Control of Demineralized Water Tank

Qahtan A Mahmood1), Amer T Nawaf 2), Maha N Esmael3), Layth T Abdulateef4) and Omar S. Dahham5)

1department of petroleum processes engineering, College of petroleum & Engineering, Tikrit University, IRAQ
2department of petroleum processes engineering, College of petroleum & Minerals Engineering, Tikrit University, IRAQ
3department of petroleum processes engineering, College of petroleum & Minerals Engineering, Tikrit University, IRAQ
4Chemical Engineering, Middle Technical University, IRAQ
5Center of Excellence Geopolymer and Green Technology (CEGeoGTech), Faculty of Engineering Technology (FETech), Universiti Malaysia Perlis (UniMAP), Level 1 Block S2, UniCITI AlamCompu, Sungai Chucun Padang Basar, 02100, Perlis, Malaysia

Corresponding author: Qahtan.adnan@tu.edu.iq

Abstract. This paper presents a temperature control of demineralized water tank system, which is widely used in industrial processes. Theoretical modeling of temperature demineralized water tank has been study by applying mass and energy balance. Results of model have been compared with experimental data. PID controller is used to control the temperature inside the process tank within operating condition. Ziegler-Nichols and Tyreus-Luyben have been used to find parameters (proportional gain, integral time and derivative time) of PI and PID controller. Integral Absolute Error (IAE) and Integral Square Error (ISE) are used to compare between performances of the controllers. The results show that PID Controller gives better performance than PI Controller for the temperature control system.

Keywords: demineralized water, PID controller, Ziegler-Nichols, and Tyreus-Luyben, Integral Absolute Error (IAE), Integral Square Error (ISE).

1. Introduction

Demineralized water is widely used in oil industrial such as boiler, heat exchanger and cooling reciprocated gas compressor [1]. Demineralization process is removed mineral such as positive and negative ions from water by using ion exchange (resin) and activated charcoal filters [2]. Arturo Rojas. et al [3] Designed PID controller for single tank system. Relay auto tuning, Ziegler-Nichols and Tyreus-Luyben methods are used to tuning the controller and compared it with response of the controller in real time. Jin–Hua She. et al [4] applied backstepping method to control the outlet of the tank such as flow rate and temperature. Mathematical model is derived and backstepping control is designed for the system. Ayla Alitnten. et al [5] studied application STPID controller to control the temperature of a semi-batch reactor. Genetic algorithm GA is used to tuning the controller. They showed that STPID with genetic algorithm is capable for giving a good control result especially if initiator added continuously to reaction. Also, the genetic algorithm can be employed to search optimum controller parameters for such very
difficult control problems. A.R. Laware. et al [6] designed conventional PID controller used Ziegler- Nichols tuning method. Many methods such as (ISE, AES, ITAE and ITSE) are used to performance the PID controller. The results showed the PID with Ziegler-Nichols method having large overshoot and settling time. R.A. Darandale .et al [7] design and implement high performance Model Predictive controller for a temperature process. The objective of the controller design is to maintain the temperature inside the process tank within a desired value. They observed that the MPC for temperature process provides optimum values of performance indices. M.S.M Aras. et al [8] used Fuzzy Logic Controller (FLC) to control the temperature inside tank within desire value. The results compared with PID controller. They showed that FLC has lower overshoot and more stability. T.kavita et al [9] showed that PID controller has less setting time and more overshoot when compared with PD and PI controller for water bath system.

In this study the application of PI and PID controller’s strategy is implemented to control the temperature demineralized water tank. Demineralized water is used for cooling compressor packing boxes, and also outer cylinder wall within range of operating temperature to prevent reduce efficiency of compressor due to rise in temperature. Ziegler-Nichols and Tyreus-Luyben has been used to find parameters (proportional gain, integral time and derivative time) of PI and PID controller. Integral Absolute Error (IAE) and Integral Square Error (ISE) are used to compare between performances of the controllers.

2. Mathematical Model

Mathematical model of demineralized water tank is derived by using mass and energy balance. The tank has one input variable power of electrical heater and one output variable temperature of demineralized water, this system is called as (signal input signal output, (SISO) system [10]. the following assumptions are being made:

a. Density and heat capacity of water are constant.
b. Level of water in tank is constant.
c. Cross sectional area of tank is constant.
d. Temperature of inlet water tank is constant (30°C).
e. Neglect the heat losses to the surrounding.

![Figure 1. Maintain constant temperature](image)

Energy balance around the tank gives:

\[
\rho \cdot c_p \cdot F_t \cdot \theta_t + Q - \rho \cdot c_p \cdot F_o \cdot \theta = \frac{d(m \cdot c_p \cdot \theta)}{dt} \quad (2.1)
\]
Since: \( m = \rho \cdot A \cdot h \)
Then
\[
\rho \cdot c_p \cdot F_t \cdot \theta_t + Q - \rho \cdot c_p \cdot F_o \cdot \theta = \rho \cdot c_p \cdot A \cdot \frac{d(\theta)}{dt}
\]
(2.2)

\[
\frac{F_t}{F_o} \cdot \theta_t + \frac{Q}{\rho \cdot c_p \cdot F_o} - \theta = A \cdot h \frac{d(\theta)}{dt}
\]
(2.3)

\[
\frac{F_t}{F_o} \cdot \theta_t + \frac{Q}{\rho \cdot c_p \cdot F_o} - \theta = A \cdot h \frac{d(\theta)}{dt}
\]
(2.4)

For steady state condition \( F_t = F_o \). Then,
\[
\frac{A \cdot h \cdot d(\theta)}{F_o} \frac{d(\theta)}{dt} + \theta = \theta_t + \frac{Q}{\rho \cdot c_p \cdot F_o}
\]
(2.5)

From assumption \( \theta_t \) is constant, and Laplace transforming for equation (2.5), we get:
\[
\left( \frac{A \cdot h}{F_o} \right) \cdot s + 1 \right] \theta(s) = \frac{Q(s)}{\rho \cdot c_p \cdot F_o}
\]
(2.6)

\[
G_{PT,A}(s) = \frac{\theta(s)}{Q(s)} = \frac{1}{\left( \frac{A \cdot h}{F_o} \right) \cdot s + 1}
\]
(2.7)

Equation (2.7) gives the transfer function of de mineralized water tank which represent the relation between the power of electric heater and temperature of outlet water. The data of mathematical model is taken in table (1).

| Table 1. Data of mathematical model |
|--------------------------------------|
| variable                            | value | units             |
| Flow Rate of Water                  | 27.8  | cm/sec           |
| Heat Capacity of Water              | 4.18  | j/g.k            |
| Density of Water                    | 1     | g/cm³            |
| Height of Water in Tank (%)         | 12    | %                |
| Cross Sectional Area of Water Tank | 240.4 | cm²              |
| Maximum Power of Electrical Heater  | 1.7   | KW               |

\[
G_{PT,A}(s) = \frac{\theta(s)}{Q(s)} = \frac{8.6}{1.73s + 1}
\]
(2.8)

From equation (2.8) we get gain of the process is 8.6 C/KW and the time constant is 1.73 min.

3. Types of Feedback Controller

Structure of feedback PID controllers used in water tank system is shown in figure (2) [11].
3.1 (Proportional Integral) PI Controller
Integral action is introduced to proportional controller \((K_C \epsilon)\) to eliminate steady state offset. The integral corrects accumulation of error. Proportional Integral controller is described by the relationship.

\[
P = K_C \epsilon + \frac{K_C}{\tau_I} \int_0^t \epsilon \, dt + P_s
\]

3.2 (Proportional Integral Derivative) PID Controller
Derivative control is added to proportional integral controllers to correct present error and reduce process oscillations. Proportional Integral Derivative is described by the relationship.

\[
P = K_C \epsilon + \frac{K_C}{\tau_I} \int_0^t \epsilon \, dt + K_C \tau_D \frac{d\epsilon}{dt} + P_s
\]

3.3 Tuning of PID Controller

3.3.1 (Ziegler-Nichols) PID Tuning Method
The Ziegler-Nichols tuning method is based on closed-loop testing (also called on-line tuning) of processes which are inherently stable, but where the system may become unstable [11]. The procedure for tuning a process according to this rule proceeds as follows [12].

- Use proportional control only and increase the controller gain until the system starts to oscillate.
- Determine the amplitude ratio at his frequency

The controller parameters of (Z-N) methods are given in table 2.

|                      | P Controller | PI Controller | PID Controller |
|----------------------|--------------|---------------|---------------|
| **Kc**               | \(K_u/2\)    | \(K_u/2.2\)   | \(K_u/1.7\)   |
| **\(\tau_I\)**      | \_           | \(P_u/1.2\)   | \(P_u/2\)     |
| **\(\tau_D\)**      | \_           | \_            | \(P_u/8\)     |

3.3.2 (Tyreus – Luyben) PID Tuning Method
The Tyreus-Luyben tuning method is applied for settings PI and PID controllers, and is similar to the procedure of (Ziegler-Nichols) tuning method [13]. (T-L) settings are dependence on ultimate gain and ultimate period as shown in Table (3).

| Settings of Tyreus-Luyben [13]               | PI Controller | PID Controller |
|---------------------------------------------|---------------|----------------|
| $K_c$                                       | $K_u/3.22$    | $K_u/2.2$      |
| $\tau_I$                                    | $2.2P_u$      | $2.2P_u$       |
| $\tau_D$                                    | __            | $P_u/6.3$      |

4. Experimental work
A schematic diagram of the experimental apparatus is provided in figure (3). 5.25 liter borosilicate glass cylindrical vessel was used as continuous tank. The tank is worked with range of temperature from 0 to 100°C and 2.5bar. The tank supplied with electrical coil heater made of stainless steel with power 1.7 KW. Pump is used to deliver the demineralized water from receiver to tank. Temperature of water tank is measured by using thermocouple type-E. All the components of the test rig are marked inside the block diagram figure (4).

Figure 3. Schematic of the water tank
5. Results and Discussion

5.1 Water Temperature Model

A step change in power of electrical heater is made from 0.8 KW to 1.36 KW and the outlet temperature of the demineralized water tank is recorded as shown in figure (5).

Response of the system is approximated as first order plus dead-time model as shown in equation (2.9). A step response is termed as (process reaction curve) [11].

\[
G_{PT,A}(s) = \frac{\theta(s)}{Q(s)} = \frac{K_p e^{-t_d s}}{\tau s + 1} \tag{2.9}
\]

Theoretical and experimental temperature models parameters are calculated from equations (2.8) and (2.9), respectively, and given in table (4).
Table 4. Temperature model parameters

| Parameters | Theoretical | Experimental |
|------------|-------------|--------------|
| $K_p$ °C/KW | 8.6 | 21.4 |
| $\tau_d$! | __ | 0.9 |
| $\tau$! | 1.73 | 12.5 |

5.2 Comparison of (Z-N), (T-L) methods

A Ziegler-Nichols and Tyreus-Luyben method consists of first finding the ultimate gain and ultimate period (minutes of cycle). The (Z-N) and (T-L) settings are then calculated from $K_u$ and $P_u$ by the formulas given in (Table 2 and 3). Parameters of the controllers obtained for these two methods are shown in table (5).

Table 5. Parameters of PI & PID controllers

| PI         | Ziegler-Nichols | Tyreus-Luyben |
|------------|-----------------|---------------|
| $K_c$      | 3.6             | 3.7           |
| $\tau_i$  | 10              | 26.4          |

| PID        | Ziegler-Nichols | Tyreus-Luyben |
|------------|-----------------|---------------|
| $K_c$      | 4.8             | 3.64          |
| $\tau_i$  | 6               | 26.4          |
| $\tau_d$  | 1.5             | 1.9           |

5.3 PID controller

In this work, PI and PID controller are applied to control the temperature of Demineralized Water Tank. Parameters of PI and PID controller from Ziegler-Nichols (Z-N) and Tyreus-Luyben (T-L) tuning methods is shown in Table (5) and then applied on Real-time water temperature tank model. Figures (6) (7) show the response of the, PI and PID controllers by using Ziegler-Nichols (Z-N) and Tyreus-Luyben (T-L) tuning methods. Set point temperature of Demineralized Water Tank is changed from 30 to 33 °C to observe the control performance. It can see from figure (8) the controller PID has lower over shoot and more stability compare with PI controllers.
Figures 6. Responses of PI controllers by using Ziegler- Nichols and Tyreus-Luyben tuning methods.

Figures 7. Responses of PID controllers by using Ziegler-Nichols and Tyreus-Luyben tuning methods.

Figures 8. Responses of PI and PID controllers by using Tyreus – Luyben tuning methods.
Errors response of the PI and PID controllers are summarized is tabulated in table (6).

| Method of tuning | IAE  | ISE  |
|------------------|------|------|
| Ziegler-Nichols  | 70.2 | 186.48 |
| Tyreus-Luyben    | 68.6 | 180.93 |

We see from table (6) the value of (IAE and IES) by using T-L tuning method is less values compare with Z-N method, and the controller has lowest value of (IAE and IES) is prefer. So PID controller gives better performance indices than PI controller.

6. Conclusion

A PI and PID Controllers are implemented to control the outlet temperature of demineralized water tank. The mathematical model has been presented in this study and compared with experimental results. Performance PI controller is compared with PID controller by using (IAE) and (ISE). The results show that performance of the PID Controller is better than PI Controller for the temperature control system.

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