

PRESSURIZER SIMULATOR

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Abstract—A dynamic two-phase imbalance mechanism model of pressurizer in pressurized water reactor (PWR) nuclear power plant was built based on some reasonable simplifications and basic assumptions. The equations of energy and mass conservation are used in obtaining a mathematical model for pressurizer operation. The pressurizer is divided into two regions, steam region and liquid region but not necessary in equilibrium with each other. Considering the influence of the spray flow, surge flow, safety valve and heater, the model of pressurizer pressure control system is established by MATLAB/Simulink in this paper. For the large overshoot, response delay and poor stability exist in the pressurizer pressure control system, an advanced model based on PID control algorithm is proposed. The simulation results were compared between two different data obtained by foreign PWR nuclear power plant simulator. All the compared data are quite similar in simulation result, hence it proves the simulation result quite accurate and yet the mathematical model obtained has proved its working principles successfully.

Keywords— PID control, Pressurizer, Simulation

INTRODUCTION

In a pressurized water reactor power plant (PWR), the basic function of pressurizer is to establish and maintain the pressure of the primary system. When it is in the steady-state operation situation in PWR power plant, the pressurizer maintains the system at a constant pressure of 10MPa. In the process of PWR power plant operation, the water level of pressurizer cannot be higher or lower. Higher level may let pressure regulation invalid. Lower level may let electric heater exposed in steam space and to burn up. Therefore, in this paper, a PID controller is proposed. PID control maintains a steady-state control law of PI control to improve the performance advantages of the system, while improving the dynamic performance with greater advantages. The system outputs can be adjusted by changing the strengths of proportional, integral and differential operations. Besides that, a mathematical model for the pressurizer of pressure control in the PWR power plant control system has been built. Based on the reasonable simplifications and assumptions, the mass and energy conservation equations of steam phase and liquid phase are set up, and a dynamic two-phase imbalance mechanism model of pressurizer in PWR power plant was built through detailed derivation. The simulation works in MATLAB/Simulink code, analogue pressurizer control process to deliver the most optimal system control parameters. The simulation results were compared with two different data that obtained by foreign PWR nuclear power plant simulator. Their

results are relatively similar. This show the results are quite good, which can reduce the overshoot and speed up system response time, and improve anti-interference ability of the system.

TABLE 1 THE SUMMARY OF PREVIOUS STUDIES

| Previous work by author | Diagram | Formulation | Result |
|----------------------------|--|---|--|
| MA Jin | H=13m,d=2.5m, two-phase mechanism | Conservation of mass and energy equations | Simulation result quite similar to measured result |
| Edmur Canzian | H=unknown,d=unknown, two-phase mechanism | Conservation of mass and energy equations | Simulation result only |
| R.Zarghami | H=15.91m,d=3.33m, three-phase mechanism | Conservation of mass and energy equations | Simulation result quite similar to measured result |
| Attila Gabor | H=unknown,d=unknown, two-phase mechanism | Conservation of mass and energy equations | Simulation result quite similar to measured result |
| Prof. Ir. F. Vanmassenhove | H=unknown,d=unknown, two-phase mechanism | Conservation of mass and energy equations | Simulation result is not so similar to measured data |

II. METHODOLOGY

The Figure 1 shows the schematic diagram of pressurizer. The pressurizer is divided into two regions, steam region and liquid region but not necessary in equilibrium with each other. Conservation of mass and energy equations are applied to each region. When full or empty the pressurizer reduces to a single region with conservation expressions for mass and energy over only the existing volume. The pressurizer includes external connections for the surge flow, for the spray and relief flow and for the heater electrical power. A separate surge line model allows bidirectional flow from or to the primary loop. As can see from the Figure 1, the pressurizer is

a vertical tank equipped with heater, spray valve, surge line valve and relief valve. When the pressurizer pressure decreases, the water from hot leg flows into the bottom of pressurizer via surge line valve. The water then mixed with the liquid in the bottom of pressurizer and activates the heater. When the steam at the upper part of pressurizer becomes superheated and the temperature increases, the coolant water from cold leg flows into the pressurizer via spray valve to cool down the steam. The relief valve is opened at the same time to release steam to atmosphere.

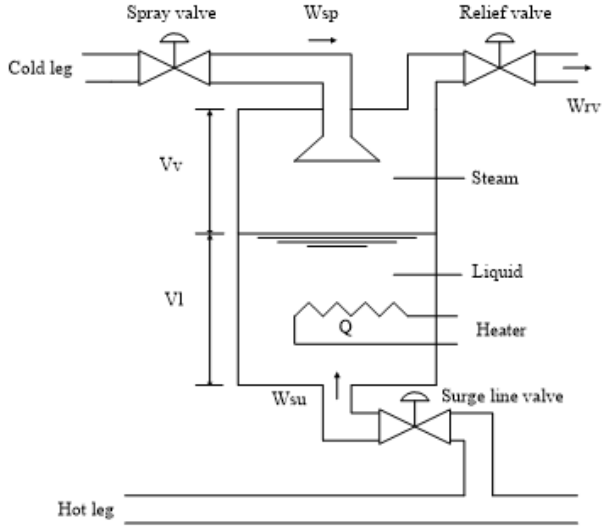


Figure 1: Schematic diagram of pressurizer

Assumptions and approximations are as below:

1. Pressure is uniform throughout the pressurizer all the time;
2. The mass exchanges between the liquid and steam interface occur in instant;
3. The spray water reaches saturation temperature before leaving the steam phase and going into the liquid phase;
4. The in-surge flow of coolant water mixes perfectly with the hot water in the bottom of surge tank;
5. The liquid phase is either saturation or overcooled, and the steam phase could be either saturation or overheating.

The pressurizer system operation can be represented in flowchart form is shown in Figure 2. This figure shows the flowchart of operation of pressurizer. Initially, the pressurizer is in normal operation. When the pressure inside the pressurizer decreases, the hot water from the hot leg enters the bottom of pressurizer via surge line valve. At the same time, the heater at the bottom of pressurizer is activated to heat the water. When the pressure inside the pressurizer starts to increase, the surge line valve is closed and heater is deactivated. Then, the coolant water from the cold leg enters the pressurizer via the spray valve that located at the top of pressurizer. At the same time, the relief valve is opened to release the steam to the atmosphere. When the pressurizer is stabilized where the pressure is maintained at the set point

level, the pressurizer operates at normal condition. If not, it will loop back as shown in Figure 2.

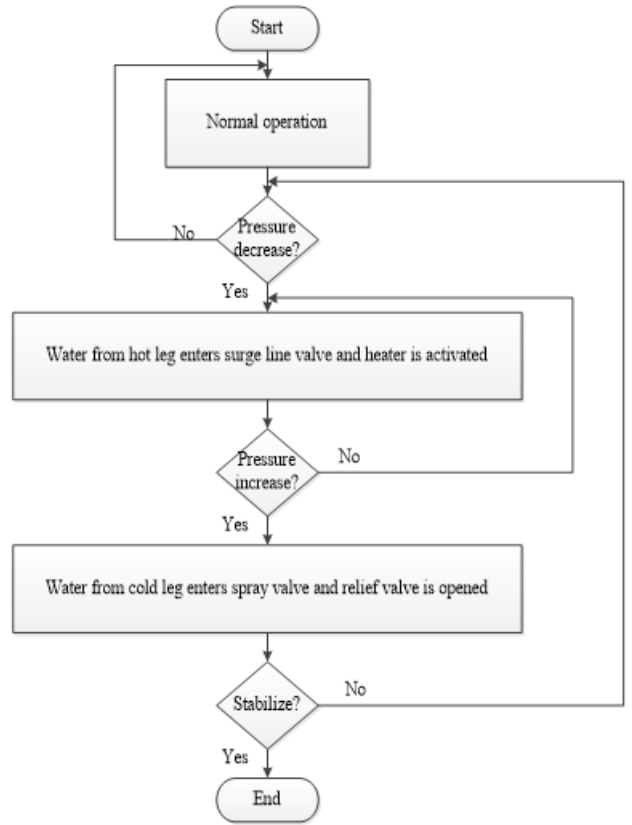


Figure 2: Block Diagram of the project

$$\frac{d}{dt}(M_{total}) = W_{su} + W_{sp} - W_{rv} \quad (1)$$

$$\frac{d}{dt}(Q_{total}) = W_{su}h_{su} + W_{sp}h_{sp} - W_{rv}h_{rv} + Q \quad (2)$$

$$\frac{d}{dt}(M_{total}) = (\rho_l V_l + \rho_v V_v)\dot{p} + (\rho_l - \rho_v)\dot{V}_l \quad (3)$$

$$\frac{d}{dt}(Q_{total}) = (\rho_l V_l h_l + \rho_v V_v h_v + \rho_l V_l \dot{h}_l + \rho_v V_v \dot{h}_v)\dot{p} + (\rho_l h_l - \rho_v h_v)\dot{V}_l \quad (4)$$

$$M = \begin{bmatrix} \rho_l V_l + \rho_v V_v & \rho_l - \rho_v \\ \rho_l V_l h_l + \rho_v V_v h_v + \rho_l V_l \dot{h}_l + \rho_v V_v \dot{h}_v & \rho_l h_l - \rho_v h_v \end{bmatrix} \quad (5)$$

$$N = \begin{bmatrix} 1 & 1 & -1 & 0 \\ h_{su} & h_{sp} & -h_{rv} & 1 \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} \dot{p} \\ \dot{V}_l \end{bmatrix} = \begin{bmatrix} \dot{\rho}_l V_l + \dot{\rho}_v V_v & \rho_l - \rho_v \\ \dot{\rho}_l V_l h_l + \dot{\rho}_v V_v h_v + \rho_l V_l \dot{h}_l + \rho_v V_v \dot{h}_v & \rho_l h_l - \rho_v h_v \end{bmatrix} \begin{bmatrix} p \\ V_l \end{bmatrix} + \begin{bmatrix} 1 & 1 & -1 & 0 \\ h_{su} & h_{sp} & -h_{rv} & 1 \end{bmatrix} \begin{bmatrix} W_{su} \\ W_{sp} \\ W_{rv} \\ Q \end{bmatrix} \quad (7)$$

$$y = [1 \quad 0] \begin{bmatrix} p \\ V_l \end{bmatrix} \quad (8)$$

The conservation of mass, $\frac{d}{dt}(M_{total})$ is formulated as equation (1) and the conservation of energy, $\frac{d}{dt}(Q_{total})$ is formulated as equation (2). By differentiating, the conservation of mass is formulated as equation (3) and the conservation of energy is formulated as equation (4). By comparing equation (1) with equation (3); and comparing equation (2) with equation (4), we get the equation (5). M is a 2×2 matrixes where the first row elements are taken from the coefficients of \dot{p} and \dot{V}_l from equation (3) and the second row elements are taken from the coefficients of p and V_l from equation (4). N is a 2×4 matrixes where the first row elements are taken from the coefficients of W_{su}, W_{sp}, W_{rv} from equation (1) and the second row elements are taken from the coefficients of $W_{su}, W_{sp}, W_{rv}, Q$ from equation (2). The N is formulated as equation (6). A state space model is implemented. By comparing with general state space model, we get new state space model as formulated as equation (7) and (8).

TABLE 2 VARIABLES VALUES OF DATA 1 AND REFERENCE TO BEREFERRED

| Variable | Value | reference |
|--|-----------------------------|-----------|
| Liquid volume, V_l | 27.5m ³ | [11] |
| Steam volume, V_v | 26.5m ³ | [11] |
| Enthalpy of spray water, h_{sp} | 1.345kJ/kg | [11] |
| Enthalpy of surge line water, h_{su} | 1.762kJ/kg | [11] |
| Enthalpy of released steam, h_{rv} | 2.482kJ/kg | [12] |
| Density of liquid, ρ_l | 0.5277kg/m ³ | [12] |
| Density of steam, ρ_v | 0.1440kg/m ³ | [12] |
| Enthalpy of liquid, h_l | 1.762kJ/kg | [11] |
| Enthalpy of steam, h_v | 2.482kJ/kg | [12] |
| Rate of change of liquid density, $\dot{\rho}_l$ | -0.3692 kg/m ³ s | [12] |
| Rate of change of steam density, $\dot{\rho}_v$ | 0.1954kg/m ³ s | [12] |
| Rate of change of liquid enthalpy, \dot{h}_l | 0.8334kJ/kgs | [12] |
| Rate of change of steam enthalpy, \dot{h}_v | -0.5360kJ/kgs | [12] |

Data 1 based on Table 2 and equation (7) and calculation shown in equations (9) – (12). By substituting equations (9) until (12) into equations (7) and (8), the new equations (13) and (14) are obtained as below. These equations will be put into the state-space parameters in SIMULINK software for simulation result.

$$\dot{\rho}_l V_l + \dot{\rho}_v V_v = (-0.3692 \times 27.5) + (0.1954 \times 26.5) = -4.975 \quad (9)$$

$$\rho_l - \rho_v = 0.5277 - 0.1440 = 0.3837 \quad (10)$$

$$\dot{\rho}_l V_l h_l + \dot{\rho}_v V_v h_v + \rho_l V_l \dot{h}_l + \rho_v V_v \dot{h}_v = (-0.3692 \times 27.5 \times 1.762) + (0.1954 \times 26.5 \times 2.482) + (0.5277 \times 27.5 \times 0.8334) + (0.1440 \times 26.5 \times -0.5360) = 5.011 \quad (11)$$

$$\rho_l h_l - \rho_v h_v = (0.5277 \times 1.762) - (0.1440 \times 2.482) = 0.5724 \quad (12)$$

$$\begin{bmatrix} \dot{p} \\ \dot{V}_l \end{bmatrix} = \begin{bmatrix} -4.975 & 0.3837 \\ 5.011 & 0.5724 \end{bmatrix} \begin{bmatrix} p \\ V_l \end{bmatrix} + \begin{bmatrix} 1 & 1 & -1 & 0 \\ 1.762 & 1.345 & -2.482 & 1 \end{bmatrix} \begin{bmatrix} W_{su} \\ W_{sp} \\ W_{rv} \\ Q \end{bmatrix} \quad (13)$$

$$y = [1 \quad 0] \begin{bmatrix} p \\ V_l \end{bmatrix} \quad (14)$$

TABLE 3 VARIABLES VALUES OF DATA 2 AND REFERENCE TO BEREFERRED

| Variable | Value | reference |
|--|----------------------------|-----------|
| Liquid volume, V_l | 25.18m ³ | [4] |
| Steam volume, V_v | 15.15m ³ | [4] |
| Enthalpy of spray water, h_{sp} | 1.595kJ/kg | [12] |
| Enthalpy of surge line water, h_{su} | 1.891kJ/kg | [12] |
| Enthalpy of released steam, h_{rv} | 2.335kJ/kg | [12] |
| Density of liquid, ρ_l | 0.4505kg/m ³ | [12] |
| Density of steam, ρ_v | 0.2020kg/m ³ | [12] |
| Enthalpy of liquid, h_l | 1.891kJ/kg | [12] |
| Enthalpy of steam, h_v | 2.335kJ/kg | [12] |
| Rate of change of liquid density, $\dot{\rho}_l$ | -0.2655kg/m ³ s | [12] |
| Rate of change of steam density, $\dot{\rho}_v$ | 0.1821kg/m ³ s | [12] |
| Rate of change of liquid enthalpy, \dot{h}_l | 0.4933kJ/kgs | [12] |
| Rate of change of steam enthalpy, \dot{h}_v | -0.4783kJ/kgs | [12] |

Data 2 based on Table 3 and equation (7) and calculation shown in equations (15) – (18). By substituting equations (15) until (18) into equations (7) and (8), the new equations (19) and (20) are obtained as below. These equations will be put into the state-space parameters in SIMULINK software for simulation result.

$$\rho_l V_l + \rho_v V_v = (-0.2655 \times 25.18) + (0.1821 \times 15.15) = -3.926 \quad (15)$$

$$\rho_l - \rho_v = 0.4505 - 0.2020 = 0.2485 \quad (16)$$

$$\rho_l V_l h_l + \rho_v V_v h_v + \rho_l V_l \dot{h}_l + \rho_v V_v \dot{h}_v = (-0.2655 \times 25.18 \times 1.891) + (0.1821 \times 15.15 \times 2.335) + (0.4505 \times 25.18 \times 0.4933) + (0.2020 \times 15.15 \times -0.4783) = -2.068 \quad (17)$$

$$\rho_l h_l - \rho_v h_v = (0.4505 \times 1.891) - (0.2020 \times 2.335) = 0.3802 \quad (18)$$

$$\begin{bmatrix} \dot{p} \\ \dot{V}_l \end{bmatrix} = \begin{bmatrix} -3.926 & 0.2485 \\ -2.068 & 0.3802 \end{bmatrix} \begin{bmatrix} p \\ V_l \end{bmatrix} + \begin{bmatrix} 1 & 1 & -1 & 0 \\ 1.891 & 1.595 & -2.335 & 1 \end{bmatrix} \begin{bmatrix} W_{su} \\ W_{sp} \\ W_{rv} \\ Q \end{bmatrix} \quad (19)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} p \\ V_l \end{bmatrix} \quad (20)$$

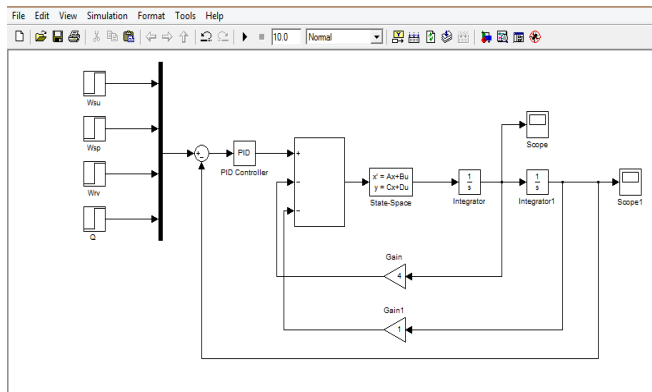


Figure 3 Block diagram of pressurizer

III. RESULT AND ANALYSIS

Figure 4 shows the state-space block parameters in SIMULINK by substituting Data 1 into parameters A, B, C and D. A=[-4.975 0.3837;5.011 0.5724] represents state transition matrix; B= [1 1 -1 0; 1.762 1.345 -2.482 1] represents input; C= [1 0] represents output and D= [0 0 0 0] represents feed-around. Figure 5 shows the simulation result with Kp=1, Ki=1 and Kd=6 which is the most accurate result for Data 1.

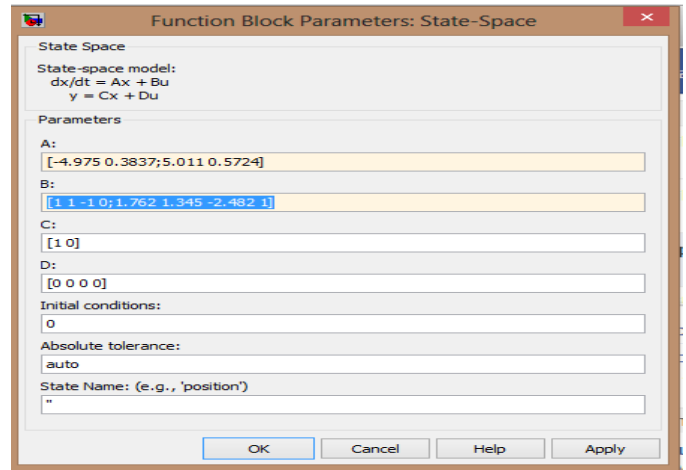


Figure 4 State-space block parameter with Data 1

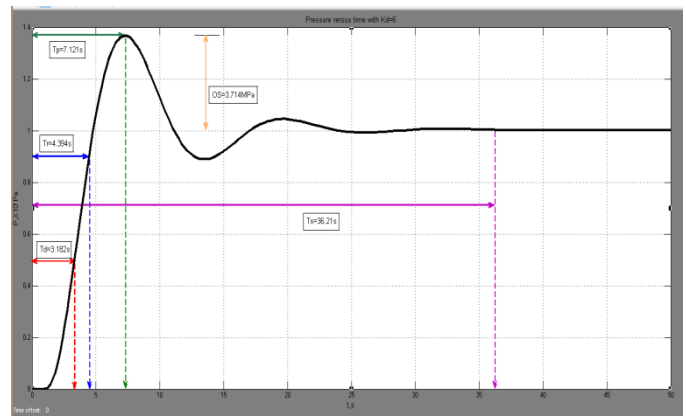


Figure 5 Pressure versus time with Kp=1, Ki=1 and Kd=6

Figure 6 shows the state-space block parameters in SIMULINK by substituting Data 2 into parameters A, B, C and D. A=[-3.926 0.2485;-2.068 0.3802] represents state transition matrix; B= [1 1 -1 0; 1.891 1.595 -2.335 1] represents input; C= [1 0] represents output and D= [0 0 0 0] represents feed-around. Figure 7 shows the simulation result with Kp=1, Ki=1 and Kd=2 which is the most accurate result for Data 2.

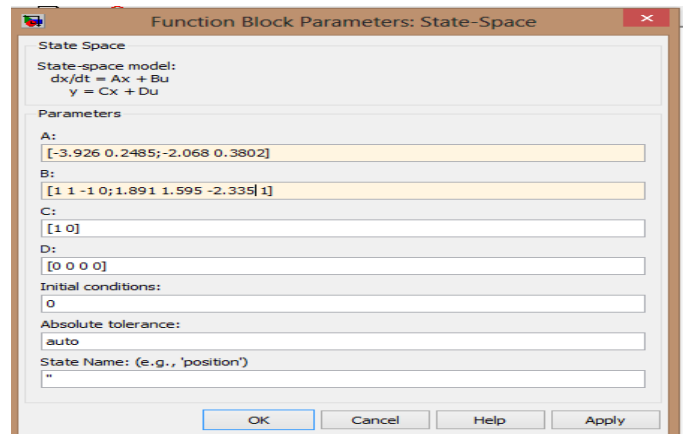


Figure 6 State-space block parameter with Data 2

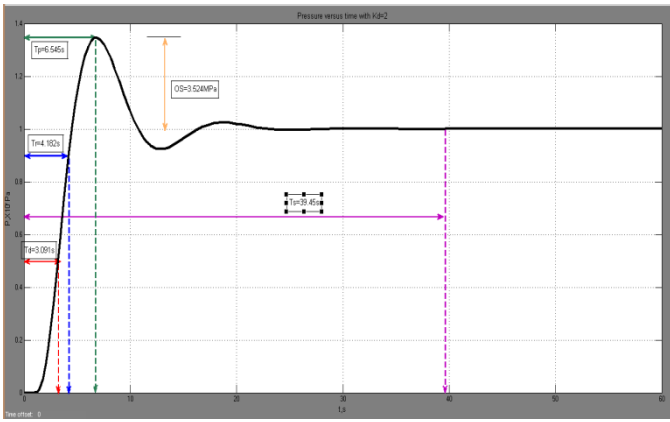


Figure 7 Pressure versus time with $K_p=1$, $K_i=1$ and $K_d=2$

TABLE 4 DELAY TIME, RISE TIME, PEAK TIME, SETTLING TIME, OVERSHOOT AND STEADY STATE ERROR OF DATA 1

| K_p | Figure | T_d (s) | T_r (s) | T_p (s) | T_s (s) | OS (MPa) | SSE |
|-------|--------|-----------|-----------|-----------|-----------|----------|-----|
| 0.5 | 4.2 | 3.696 | 4.783 | 7.826 | 60.87 | 5.158 | 0 |
| 1 | 4.3 | 3.261 | 4.565 | 7.391 | 35.65 | 3.810 | 0 |
| 2 | 4.4 | 2.826 | 3.913 | 5.870 | 38.70 | 2.095 | 0 |
| K_i | | | | | | | |
| 0.5 | 4.5 | 3.696 | 6.087 | 10 | 53.91 | 0.9524 | 0 |
| 1 | 4.6 | 3.261 | 4.565 | 7.391 | 35.65 | 3.810 | 0 |
| 2 | 4.7 | 2.963 | 3.704 | 5.926 | 115.2 | 7.765 | 0 |
| K_d | | | | | | | |
| 4 | 4.8 | 3.030 | 3.939 | 6.061 | 90.61 | 5.474 | 0 |
| 5 | 4.9 | 3.091 | 4 | 6.545 | 47.82 | 4.200 | 0 |
| 6 | 4.10 | 3.182 | 4.394 | 7.121 | 36.21 | 3.714 | 0 |

TABLE 5 DELAY TIME, RISE TIME, PEAK TIME, SETTLING TIME, OVERSHOOT, AND STEADY STATE ERROR OF DATA 2

Table 4 shows the delay time, rise time, peak time, settling time, overshoot and steady state error of Data 1 and Table 5 shows the delay time, rise time, peak time, settling time, overshoot and steady state error of Data 2. The analysis is based on the characteristics of input and output responds (rise time, peak time, overshoot, settling time and steady-state error). Rise time, T_r refers to the time required for a signal to change from a specified low value to a specified high value. Typically, these values are 0-10% and 90% of the step height. Peak time, T_p is the time required for the response to reach the first peak of the overshoot. Settling time, T_s is the time elapsed from the application of an ideal instantaneous step input to the time at which the output has entered and remained within a specified error band. Overshoot, OS is when a signal or function exceeds its target. It is often associated with ringing. Steady state error defined as the difference between the desired final output and the actual one when the system reaches a steady state, when its behaviour may be expected to continue if the system is undisturbed, to determine the suitable parameter for PID controller used to control the operation of pressurizer, trial and error method on tuning process is utilised. Firstly, must determine the appropriate value of proportional gain, K_p (integral gain, K_i and

derivative gain, K_d held constant). After determining the value of K_p , the next step is to determine the appropriate value of integral gain, K_i (proportional gain, K_p and derivative gain, K_d held constant). After determining the value of K_i , the last step is to determine the appropriate value of derivative gain, K_d (proportional gain, K_p and integral gain, K_i are held constant).

TABLE 6 COMPARISON OF DELAY TIME, RISE TIME, PEAK TIME, SETTLING TIME, OVERSHOOT AND STEADY STATE ERROR BETWEEN DATA 1 AND DATA 2

| | T_d (s) | T_r (s) | T_p (s) | T_s (s) | OS (MPa) | SSE (s) |
|--------|-----------|-----------|-----------|-----------|----------|---------|
| Data 1 | 3.182 | 4.394 | 7.121 | 36.21 | 3.714 | 0 |
| Data 2 | 3.091 | 4.182 | 6.545 | 39.45 | 3.524 | 0 |

Table 6 shows the comparison of delay time, rise time, peak time, settling time, overshoot and steady state error

| K_p | Figure | T_d (s) | T_r (s) | T_p (s) | T_s (s) | OS (MPa) | SSE (s) |
|-------|--------|-----------|-----------|-----------|-----------|----------|---------|
| 0.5 | 4.13 | 3.478 | 4.348 | 6.739 | 64.57 | 5.684 | 0 |
| 1 | 4.14 | 3.030 | 3.788 | 6.061 | 33.64 | 4.200 | 0 |
| 2 | 4.15 | 2.727 | 3.273 | 4.727 | 52.73 | 3.143 | 0 |
| K_i | | | | | | | |
| 0.5 | 4.16 | 3.455 | 5.636 | 10.00 | 36.73 | 0.9000 | 0 |
| 1 | 4.17 | 3.091 | 4.182 | 6.727 | 39.45 | 3.524 | 0 |
| 2 | 4.18 | 2.778 | 3.333 | 5.556 | 78.33 | 7.529 | 0 |
| K_d | | | | | | | |
| 1 | 4.19 | 3.030 | 3.788 | 6.061 | 33.64 | 4.200 | 0 |
| 2 | 4.20 | 3.091 | 4.182 | 6.545 | 39.45 | 3.524 | 0 |
| 3 | 4.21 | 3.261 | 4.565 | 7.609 | 59.57 | 3.429 | 0 |

between Data 1 and Data 2. All the compared variables are quite similar, hence it proves the simulation result quite accurate and yet the mathematical model obtained has proved its working principles successfully.

IV. CONCLUSION AND RECOMMENDATION

It can be concluded that the three objectives in carrying out this project was achieved as shown in the results and analysis. The first objective is to formulate a mathematical model of a pressurizer. The mathematical model represents a transfer function (single-input single-output) and state-space (multi-input multi-output). The mass flow, energy, water level and pressure are either input or output. To simulate the mathematical model of a pressurizer using MATLAB and SIMULINK is the second objective where the simulation results were compared with two different data that obtained by foreign PWR nuclear power plant simulator. The parameter of state-space block in SIMULINK is changed by substituting two different set of data which fit the parameter A, B, C and D. The results are relatively similar. The third objective is to analyse a simulation result of a pressurizer. The analysis based on characteristics of input and output responds (rise time, peak time, overshoot, settling time and steady-state error). This shows the results are quite good, which can reduce the overshoot and speed up system response time, and improve anti-interference ability of the system. In this project there are some improvements that could be made to improve

system performance For example, changing the conventional PID controller with advanced model such as RBF tuning PID and Fuzzy-PID Control that used by previous work that has better capability in reducing the overshoot, disturbance and the response time. Besides that, improvement can also be done by using hot leg with better heat conducting wall material for better heat dissipation purpose.

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