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Modelling of an interacting series process for rector cooling system using system identification method

Nur Aina Mohammad Abdul Aziz [1], Azura Che Soh [1, *], Ribhan Zafira Abdul Rahman [1] and Julia Abdul Karim [2]

[1] *Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor Darul Ehsan, Malaysia.*
[2] *Reactor Technology Centre, Technical Support Division, Malaysian Nuclear Agency, 43000 Kajang, Selangor.*

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Abstract

This research presents the modelling of cooling system plant in the TRIGA PUSPATI reactor (RTP). The RTP cooling system involves the interacting series process which are reactor model and heat exchanger model. The behaviour process is complex due to the nonlinearity, uncertainty, and time variation of the system. Due to the nonlinearity and interacting series process of system, the numerical algorithm for subspace state space system identification (N4SID) was proposed in the modelling of RTP cooling system. However, the model was converted to the transfer function form. The output response from the simulation model of RTP cooling subsystems were analysed by comparing the model with the real operational data. The responses of the model were within the respective range of a good model data. The residual analysis for each output was also calculated. The comparison and residual analysis were done to validate the model accuracy to determine the behaviour of the model. Overall, the model accuracy assessment shows that all models are still fit in the good model region (<10%) and has a good representation of a real plant.

Keywords: Reactor cooling system; System identification; Interacting series process; Residual analysis

1 Introduction

Reactor TRIGA PUSPATI reactor (RTP) is the only nuclear research reactor in Malaysia. TRIGA stands for training, research, isotope production, and general atomic. The RTP has been operating for more than 35 years since its first criticality on June 28, 1982[1]. Its cooling system consists of primary and secondary coolant circuits. The primary coolant circuit comprises the reactor tank, three primary pumps, two plate type heat exchangers, filters, and associated piping and valves [2]. Reactor is the main component in the nuclear power plant. When rod control moves up and down, the neutrons population changes respectively. This has caused the temperature of the reactor changes and affects its reactivity [3]. Therefore, heat exchanger is needed to control the temperature. Heat exchanger is a heat transfer device that exchanges heat between two or more fluids. It has been widely used in many applications such as steam generator, condenser, radiator, evaporator, cooling tower, heater, and air-conditioning systems [4]. The type of heat exchanger used in the RTP cooling system is the plate type heat exchanger.

In this research, the RTP cooling system was modelled using system identification method. System identification is a method for creating mathematical models of dynamic systems from measured input–output data. The method lets researchers to create and use models of dynamic systems from the first principles or specifications [5]. The method is done by the black box modelling because it is useful when the main purpose of the model is to fit the data regardless of the mathematical structure of the model [6]. A series of systems commonly occurs in process plants that involve the

* Corresponding author: Azura Che Soh
Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor Darul Ehsan, Malaysia.

assembly of heat exchanger, chemical reactor, product cooling, and product separation. There are two categories of the system with structures, which are interacting and non-interacting series processes. The system identification is a practical approach to construct a multiple-input multiple-output (MIMO) state space model based on input-output data [7].

Over the years, many components replacement approaches and modifications have been done to sustain the integrity and safety of RTP. There are many challenging issues regarding the RTP, such as time variation and uncertainty. Therefore, a model of the RTP cooling system was developed for further system monitoring. This research aims to carry out an analysis for a more rigorous understanding of the RTP cooling system. The model simulation was validated by the system identification of interacting series process plant using the numerical subspace state space system identification (N4SID). The N4SID method was proposed because the RTP cooling system has a typical structure of interacting series process where the strong influences between subsystem variables occur in both ways. The process also shows some nonlinearities either in the overall response, such as the shiftiness of output variables, or in the response of individual units from the respective inputs [7,8].

2 Overview of Reactor Cooling System

Figure 1 shows the components in the reactor cooling system include valves, reactor, demineraliser, heat exchanger, and sensors. Once the reaction inside the reactor starts, the temperature rises and water goes into the heat exchanger. When the temperature drops, the water flows back as coolant water for the reactor. T001 is the temperature sensor that detects the temperature of water in the reactor. However, T001 was ignored in the modelling parameter because it has the same temperature value as that of T002. P001, T002, T003, and F001 were considered before entering the heat exchanger. These sensors are the inlet measurement of hot fluid heat exchanger, while P004 and T005 are the sensors for outlet measurement. P003, T004, and F002 are the sensors for the inlet measurement of the cold fluid heat, while P002 and T003 are the sensors for the outlet measurement. Figure 2 shows the block diagram of RTP cooling system created based on Figure 1. It is a multi-input multi-output (MIMO) system constructed from three types of sensors, such as flow rate sensor, temperature sensor, and pressure sensor.

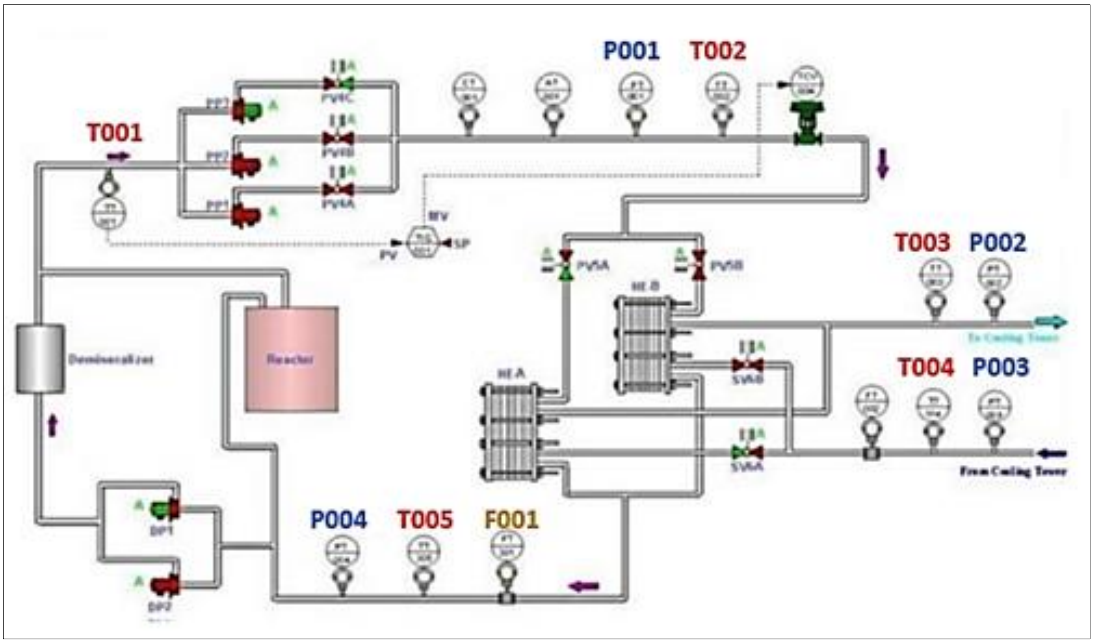


Figure 1 Overview of reactor cooling system

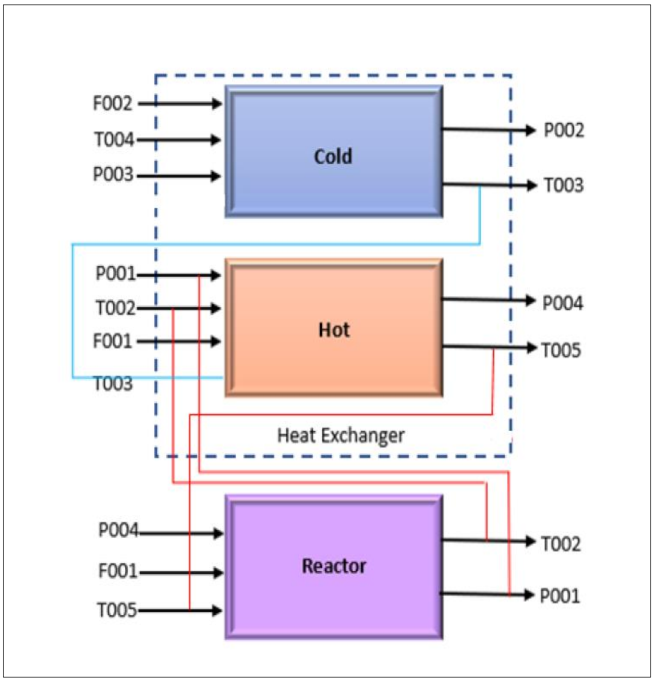


Figure 2 Block diagram of reactor cooling system

3 Modelling of Reactor Cooling System

The RTP cooling system was modelled using the system identification toolbox in MATLAB. The flowchart of system modelling is shown in Figure 3. Data collection was done by accumulating the real operation data from RTP. There are five temperature sensors known as T001, T002, T003, T004, and T005, four pressure sensors known as P001, P002, P003, and P004, and two flowmeter sensors known as F001 and F002. Then, the data were normalised. Normalisation is used to scale a mining of data that have multiple attributes of different range. The data need to be in a smaller range to obtain a good data model. Furthermore, it is essential to have precise measured data because it can affect the behaviour of the system. The modelling approaches of the system were done using the system identification with black box modelling method.

The model structure for this system was selected using the N4SID algorithm which is interpreted in a transfer function. The development of the model is based on Eq. (1) [7]:

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} \left(1 - G_{y-12}G_{y-21}\right)^{-1} \left[\begin{bmatrix} G_{11} \\ G_{21} \\ G_{31} \end{bmatrix}^T + G_{y-12} \begin{bmatrix} G_{12} \\ G_{22} \\ G_{32} \end{bmatrix}^T \right] \\ \left(1 - G_{y-12}G_{y-21}\right)^{-1} \left[\begin{bmatrix} G_{12} \\ G_{22} \\ G_{32} \end{bmatrix}^T + G_{y-21} \begin{bmatrix} G_{11} \\ G_{21} \\ G_{31} \end{bmatrix}^T \right] \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} \quad \ldots\ldots\ldots\ldots(1)$$

Where G_{ij} represents the transfer function of i_{th} input to j_{th} output while G_{y-ij} represents the transfer function of i_{th} output to j_{th} output.

One of the important aspects to consider when choosing a model structure is the linearity of the system. Usually, a linear model is acceptable to define the system dynamics accurately. If the linear model cannot fit the data, only then nonlinear data model structure is chosen. After that, model estimation was done by the system identification in MATLAB. If the order selected does not satisfy the model validation requirement where if the mean squared error (MSE) is low, the model is considered good and if it is not, the model will have to be troubleshooted again. For model validation, the model quality can be evaluated by comparing the model response to the measured response, analysing residuals, and analysing model uncertainty.

Reactor is defined as an important heating element of the RTP cooling system. From Figure 2, the responses change on each of the sensor and considering the interaction from one to another output variable. The figure shows the flow of reactor where the inputs of the reactor are from P004, T005, and F001 where it shows the coolant water flows into the reactor. The output is the T002 sensor that shows the temperature of the coolant water rise after the reaction happens inside the reactor. The dynamics of the reactor subsystem is represented in Figure 4.

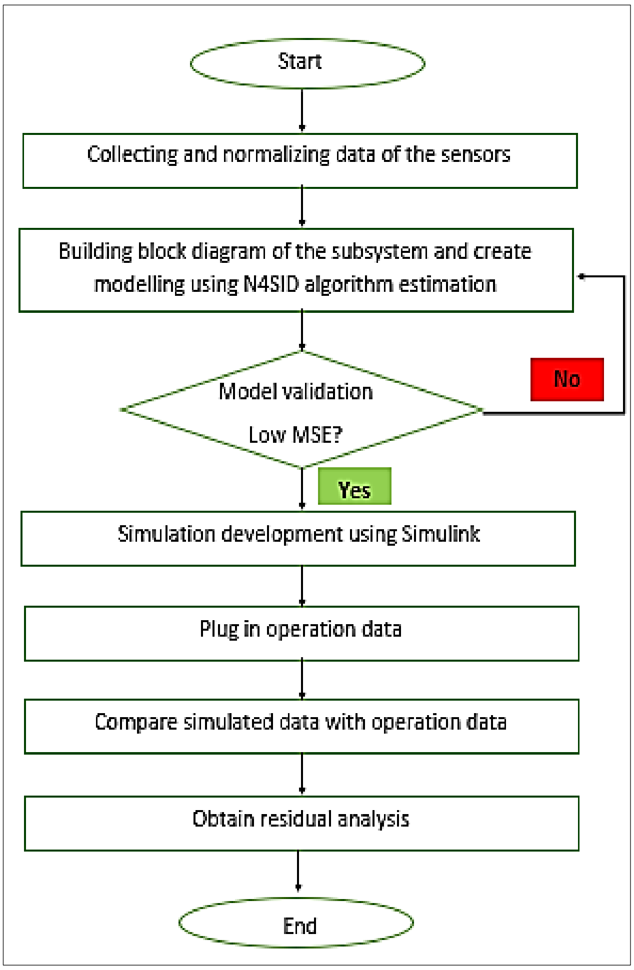


Figure 3 Flowchart of reactor cooling system modelling

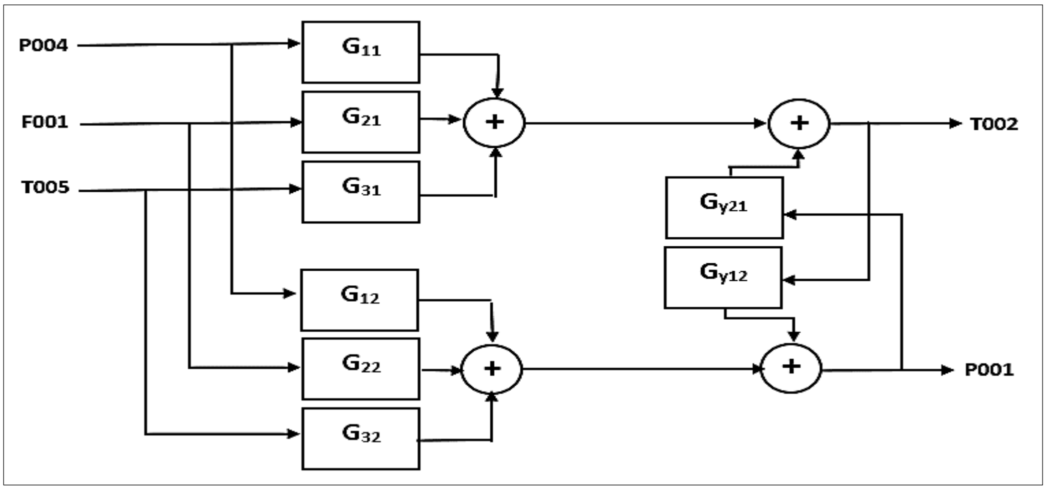


Figure 4 Dynamic of reactor subsystem

Heat exchanger is used to regulate the temperature of the coolant water in the reactor. Heat that comes out from fluid that flowing into heat exchanger minus heat coming out from fluid flowing out of heat exchanger minus heat loss to surrounding will give the rate of change energy of heat exchanger. Based on analyses from heat exchanger block diagram as shown in Figure 2, the responses changes on each of the sensor and considering the interaction from one to another output variable. The dynamics of the heat exchanger of cold and hot fluid are represented in Figure 5 and Figure 6, respectively. The dynamics subsystem was modelled using Eq. (1) with a few modifications of four inputs and two outputs. To acquire the transfer function stated in the equation, the system identification was used and the same method applied to the reactor was applied to both heat exchanger models.

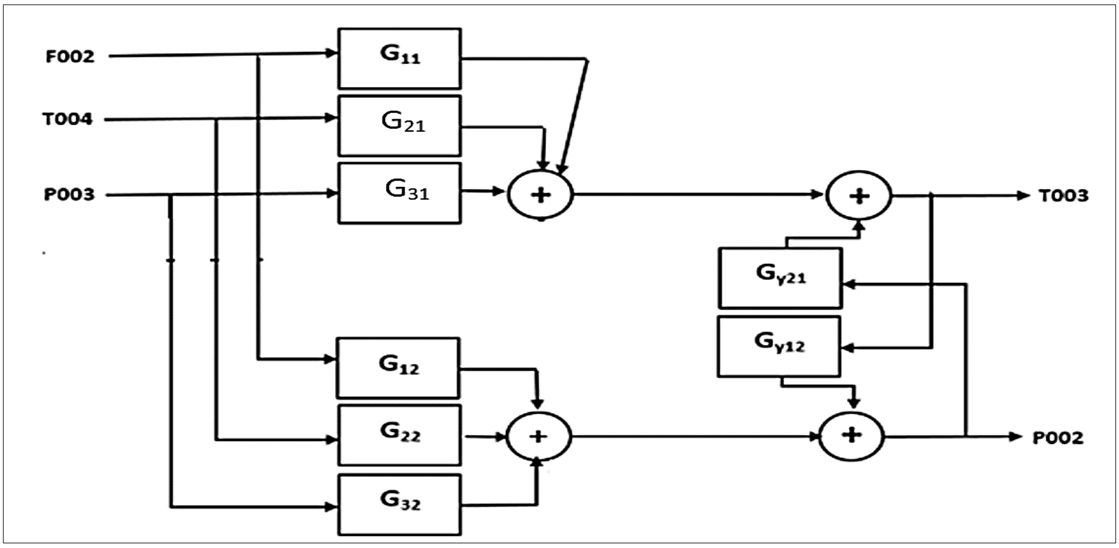


Figure 5 Dynamics of heat exchanger for cold fluid subsystem

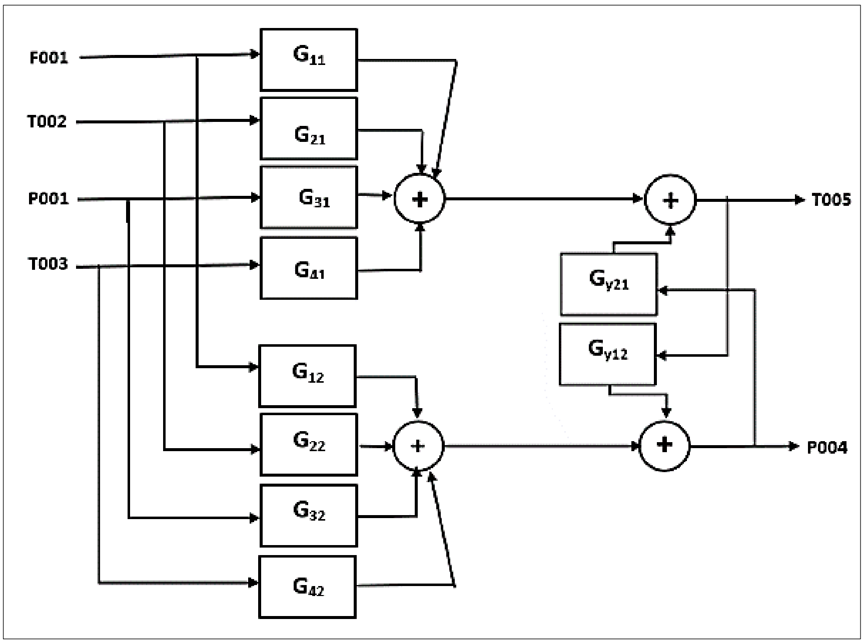


Figure 6 Dynamics of heat exchanger for hot fluid subsystem

4 Results and discussion

Validation is the most important aspect of this research to determine whether the modelling could fit the data to optimise the system. The three subsystems in the cooling system were modelled using system identification (SI) toolbox by applying the system identification of interacting series process to the RTP cooling system. The data object for the three subsystems was created into the SI toolbox to obtain the transfer function. Then, the transfer function was plugged into the Simulink model as shown in Figure 7, Figure 8 and Figure 9.

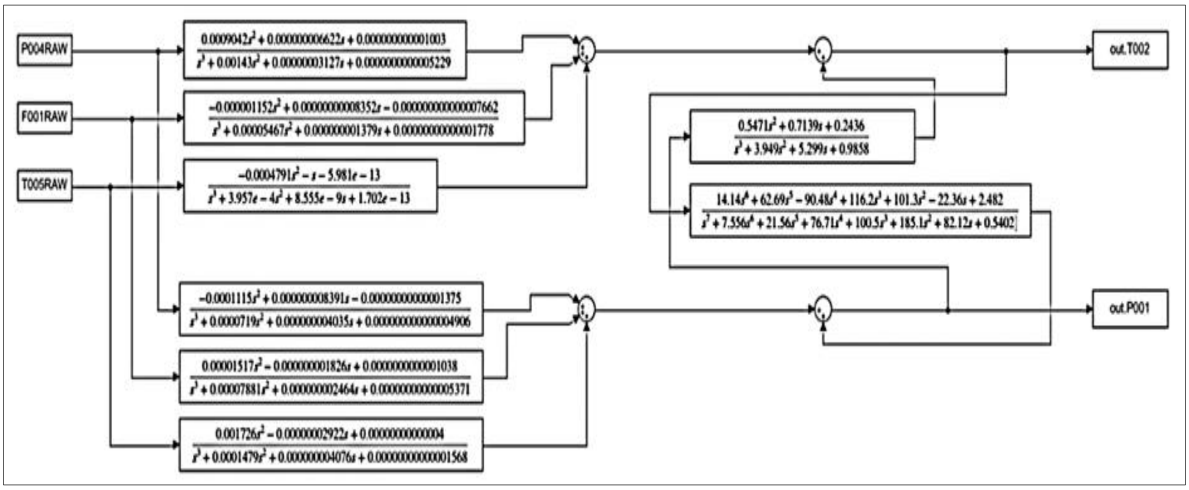


Figure 7 Simulink model for reactor subsystem

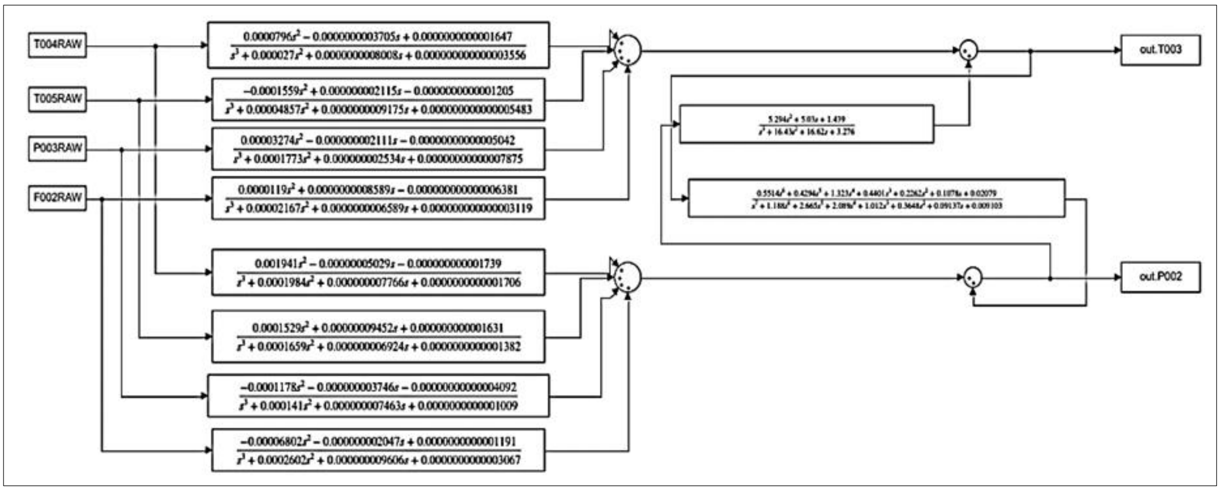


Figure 8 Simulink model of heat exchanger for cold fluid subsystem

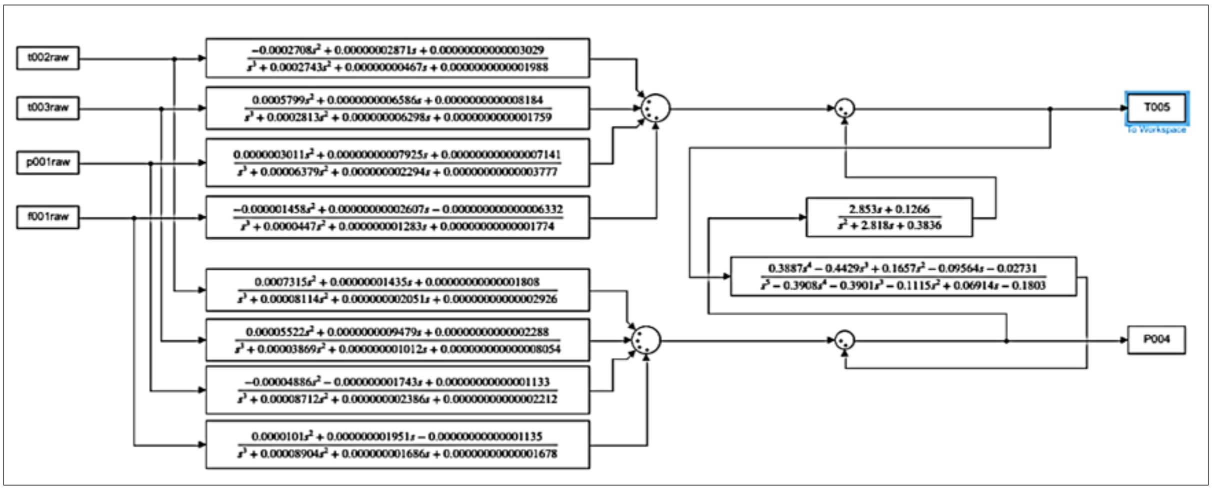
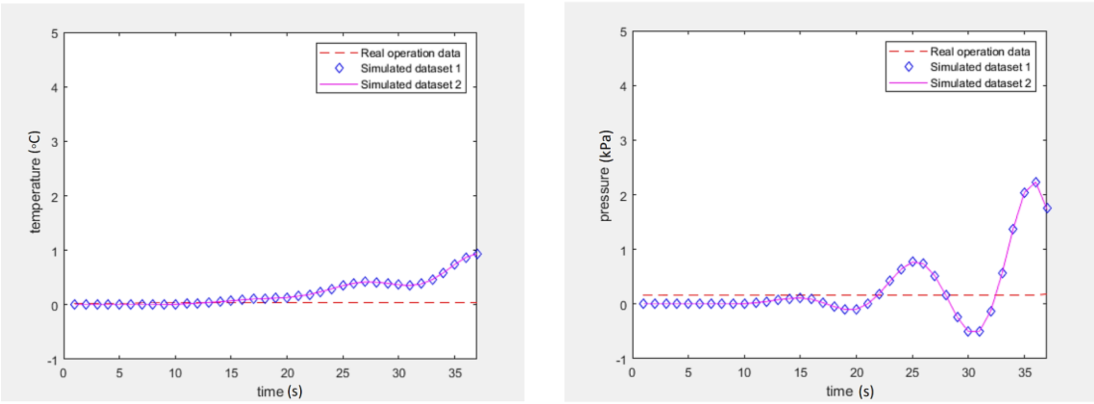


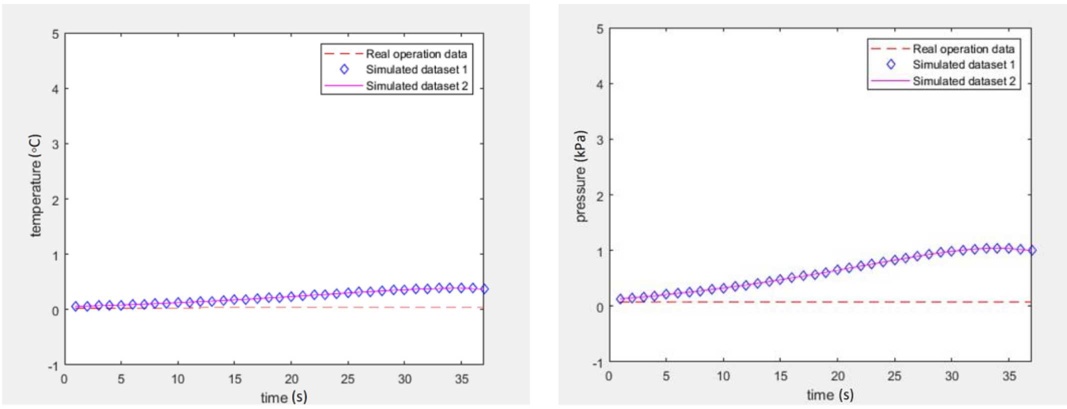
Figure 9 Simulink model of heat exchanger for hot fluid subsystem

4.1 Comparing Model Response to Real Operation Response



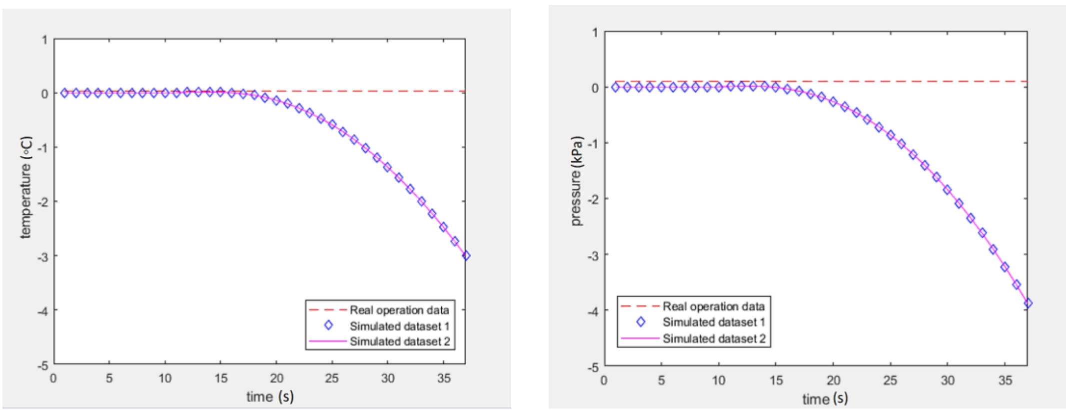
(a) (b)

Figure 10 Comparison of simulated response and real operating data response for output reactor (a) T002 and (b) P001



(a) (b)

Figure 11 Comparison of simulated response and real operating data response for output heat exchanger-cold (a) T003 and (b) P002



(a) (b)

Figure 12 Comparison of simulated response and real operating data response for output heat exchanger-hot (a) T005 and (b) P004

The model was validated by comparing the model response (Datasets 1 and 2) with the real operation response. If the result is different from the real operation response, further troubleshooting needs to be carried out to solve the problem. From Figure 10, T002 and P001 of the reactor model show excellent fit towards the target data, proving that the model accuracy is high. Figure 11 show that the responses of P002 and T003 are in the range and almost completely fit the real operating data. Meanwhile, Figure 11 imply that T005 and P004 started with high model accuracy but diverted a little bit at the end of the simulation. Overall, all the plotted model responses fit the real operation response.

4.2 Residual Analysis

According to [9] on the model accuracy assessment, Rank A indicates the residual mean of less than 10%, whereas Rank D indicates the residual mean of more than 50%. If the residual mean is in the range of 20% to 30%, it is ranked as B. The rest of the residual is ranked as C. Based on Table 1, the overall output response has achieved a good model performance with all residual means were ranked A. However, Datasets 1 and 2 for P004 and Datasets 1 and 2 for T005 have larger residual but still complies within the A ranked model.

Table 1 Summary of RTP model performance

Output	Data	Residual Mean (%)	Rank
T002	Dataset 1	0.6728	A
	Dataset 2	0.4219	A
T003	Dataset 1	0.1958	A
	Dataset 2	0.1955	A
T005	Dataset 1	3.4574	A
	Dataset 2	3.4578	A
P001	Dataset 1	0.4138	A
	Dataset 2	0.4219	A
P002	Dataset 1	0.5401	A
	Dataset 2	0.539	A
P004	Dataset 1	4.5778	A
	Dataset 2	4.579	A

A=good, B=acceptable, C=marginal, D=poor

5 Conclusion

This research conducted an analysis for a more rigorous understanding of the RTP cooling system model simulation through validation system identification of interacting series process plant. The way to develop the model was acquired by referring to the MIMO model structure equation that was implemented into the dynamics of the subsystem. In this modelling, the subspace identification method using N4SID algorithm is a more suitable method for constructing a state space model of an interacting series process rather than prediction error method, indicated by smaller identification and validation errors. To obtain the transfer function of the respective dynamics, system identification toolbox was implemented as the mathematical modelling of RTP. The mechanism of the cooling system was investigated properly and the block diagram of the respective subsystem was also acquired.

Output response from the Simulink-MATLAB simulation model of the RTP cooling subsystem was analysed by comparing it with the real operation data. The simulation shows that all model responses were in the respective range of the good model data. The residual analysis for each output was also calculated. The comparison and the residual analysis were made to validate the model accuracy to determine the behaviour of the model. Based on the residual analysis, the reactor output response and heat exchanger for cold fluid output response have the residual mean of less than 1%, whereas the heat exchanger for hot fluid output response has the residual mean of 3.5% and 4.6% for T005 and P004, respectively. Overall, all models still fit in the good model region (<10%).

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declare that is no conflict of interest of this research work.

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