Shell and Tube Heat Exchanger, Empirical Modeling Using System Identification

Firew Dereje Olana[1(✉)], Beza Nekatibeb Retta[2], Tadele Abera Abose[3], and Samson Mekibib Atnaw[2]

[1] Faculty of Engineering and Technology, Mettu University, Mettu, Ethiopia
firew.dereje@gmail.com
[2] Addis Ababa Science and Technology University, Addis Ababa, Ethiopia
{beza.nekatibeb,samson.mekbib}@aastu.edu.et
[3] Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia
tadenegn@gmail.com

Abstract. In many industrial process and operations, shell and tube heat exchangers are one of the most important thermal devices that sustained a wide range of operating temperature and pressure. However, the nonlinearity nature of the heat exchangers, and the exclusions of disturbances and uncertainties in linear models, makes the task of mathematical modeling of the system becomes challenging. Here, the solution followed for such problems is experimentally finding linear mathematical model that includes the effect of disturbances. To avoid problem of the system nonlinearities, the overall system is partitioned in to three operating ranges. Then, experimentally generated input-output data has been used in the MATLAB in order to identify the three partitioned system models. For each particular operating range, input-output data has been collected and analyzed using MATLAB environment. After iterative procedure, the plant models are obtained with satisfactory accuracy and residual analysis within range of limits. The results showed that the first test, the second test and the third test models have the best fit of 80.28%, 81.16% and 80.86% respectively. Finally, the overall model is approximated to single linear model that represent all operating ranges.

Keywords: Heat exchanger · System partitioning · System identification · Linear approximation

1 Introduction

In many engineering processes, such as nuclear plant, petrochemical, food processing, beverage and pharmaceutical industries heat exchangers are important thermal devices and they are usually characterized by high energy demands [1, 2, 6]. There are different types of heat exchangers that can be used in industries but the most commonly used ones are shell and tube heat exchangers. Most industrial processes require acceptable model for such devices. There are some methods of determining a model for a system, namely first principle and empirical models [3, 4]. First principle modeling involves accepted mathematical and scientific equations that describe the physics and principle of a given

N. G. Habtu et al. (Eds.): ICAST 2019, LNICST 308, pp. 548–556, 2020.
https://doi.org/10.1007/978-3-030-43690-2_40

process. The accuracy of this method increases with high level understanding of the physical system and the insertion of dynamic equation which affects the process, but practically it is difficult to take all dynamics into account. On the other hand, empirical modeling provides a way to handle unmolded dynamics and uncertainties [3, 5, 7].

Heat exchangers are nonlinear with changing process gains, time constants, and dead times. In spite of this fact, it has been traditionally modeled using linear techniques, which use constant gains, time constants and dead times. The heat exchangers have different gain, time constant and dead time at different range of flow rate, thus, the model of the system is time variant [5]. Many researchers have used linear time invariant model without inclusion of unmolded dynamics and uncertainty, this makes the system difficult to control [15–17]. In order to have the disturbance model of the system the experimental conduct has to be done between disturbance input to output controlled variable (Fig. 1).

a) b)

Fig. 1. (a) Hot water generator (b) Shell and tube heat exchange

2 Experimental Design and System Identification

The experiment is conducted using pilot plant of shell and tube heat exchanger. In the beginning, the partitioning strategy has been done, that is experimentally partitioning based on the flow rate [8]. This experiment takes 200 L/h of cold water or disturbance variable, hot water input as manipulated variable and cold water output as controlled variable. The Experiment is performed by varying the manipulated variable flow rate from 150 L/h up to 450 L/h. The range of the flow rate is determined by practical partitioning and capacity of the heat exchanger, for instance there is no significant model difference at 1 L/h to 150 L/h. Therefore, the remaining ranges also performed in the same way. In order to obtain the disturbance model, applying the input signal through disturbance input, and collect the data accordingly. The dimension of the heat exchanger is 1.5 × 0.7 × 2 m including its stand and measurement accessories. The input for the system is pseudo random signal with different amplitude. The experimental specifications are shown in Table 1. A separate data has been collected for model training and validation. The input-output signals for model training are shown in Fig. 2a, b and c and for model validation are shown in Fig. 3a, b, and c.

Table 1. System identification experimental specification

No̲ of tests	Hot water flow rate (L/h)	Cold water flowrate (L/h)	Hot water temperature (°C)	Cold water temperature (°C)
Test one	150	200	42	28
Test two	300	200	48	28
Test three	450	200	40	28

For test one, the input data and validation data has been taken 315 with 1 s sample time. For test two, the input data and validation data has been taken 461 with 1 s sample time. For test three, the input data has been taken 462 with 1 s sample time and 460 validation data. In all the three cases the effect of the disturbance is included during experimenting.

3 Linear Approximation of Multiple Models

The idea of multiple modeling is to approximate a nonlinear system with a set of relatively simple local models valid in certain operating regions. In order to have one linear model that represents overall operating range the weighted sum of the individual models has to be calculated as following [9–14].

$$\mu_P = \frac{\frac{1}{\epsilon_p(t)}}{\sum_{j=1}^{m} \frac{1}{\epsilon_j(t)}} \tag{1}$$

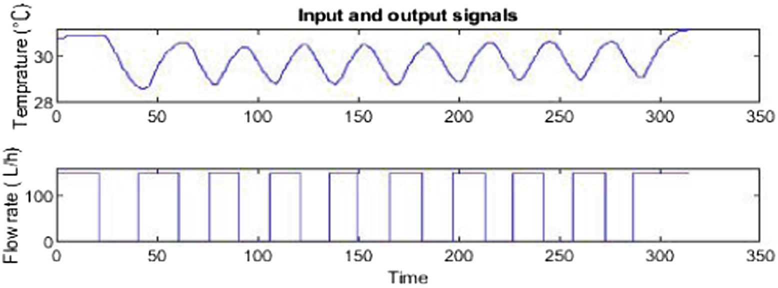
$$X(k+1) = \sum_{P=1}^{m} \mu_P A_P X(k) + \sum_{P=1}^{m} \mu_P B_P U(k) \tag{2}$$

$$Y(k) = \sum_{P=1}^{m} \mu_P C_P X(k) \tag{3}$$

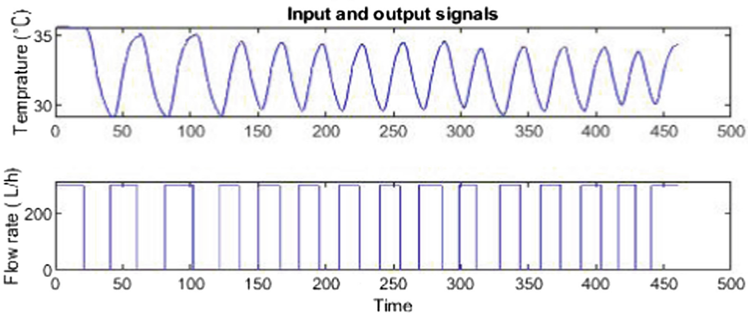
Where μ_P is the weighted function, $\epsilon_p(t)$ indicates the error between the system output value and the estimated output value of each linear model and, m is number of linear models.

4 Result and Discussion

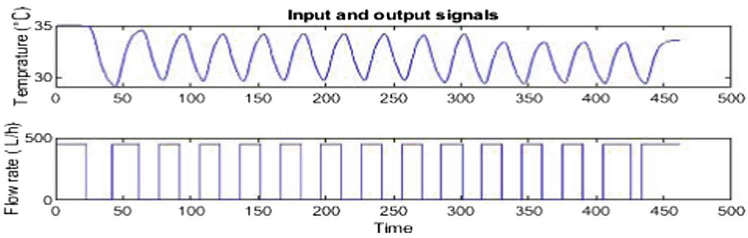
The aim this paper is finding linear model for shell and tube heat exchanger using empirical modeling. The models obtained from the response for input signals are identified



(a)



(b)



(c)

Fig. 2. Input and output signals of test one, test two and test three

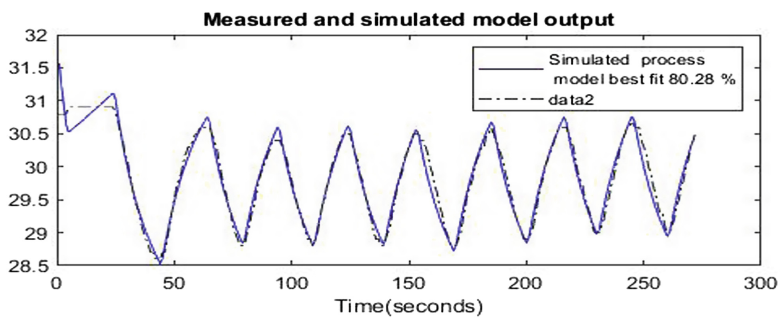


Fig. 3. The simulated and validation data output of test one

using process model (transfer function model). After reiterative procedure the model for the three tests are attained with different percentage of accuracy. Figures 3, 4, and 5 illustrated the output models using the validation data. Figures 6, 7, and 8 illustrate residual analysis test one, test two and test three respectively, the residual analyses are shown in 99% confidence interval. The residual analysis provides the information to accept the model. If the residual analysis exists between the limit line the model is acceptable. The variation in the simulated and validated data in the range of 0–50 s is because of the input and validation data has been collected in different days with different room temperature, this cause little variation in simulated and validation data (Tables 2 and 3).

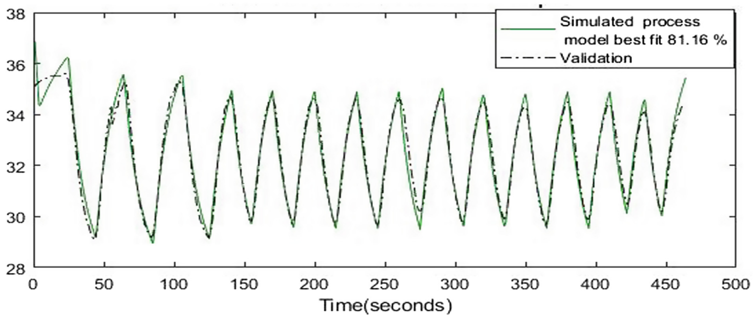


Fig. 4. The simulated and validation data output of test two

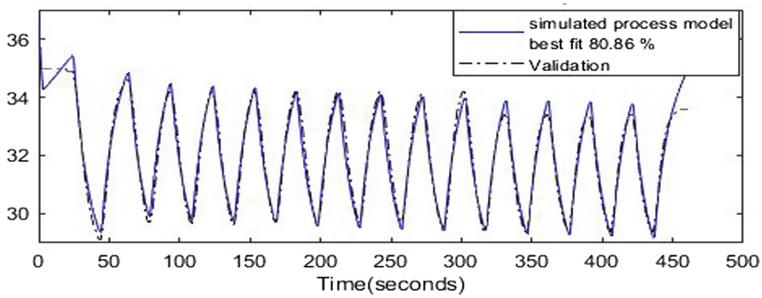


Fig. 5. The simulated and validation data output of test three

The linear approximation of the non-linearity system has to be calculated in the following equations. The overall system has been partitioned in to three regions based on manipulated variable of flow rate. In order to have one linear model that represents overall operating range the weighted sum of the individual models as following. The heat exchanger models are divided in to three regions with accuracy of 80.28%, 81.16%, and 80.86%. Therefore, the error of the three models are listed as follow:

$$\epsilon_1 = 0.1769,\ \epsilon_2 = 0.1381,\ \epsilon_3 = 0.1914$$

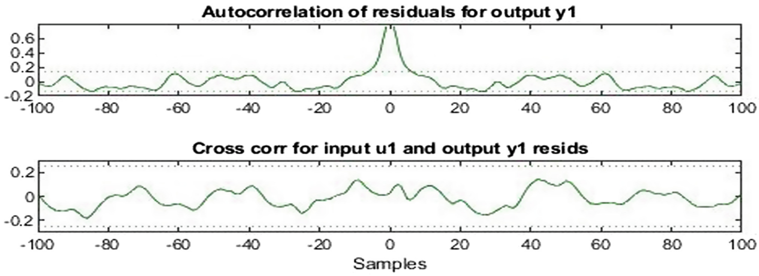


Fig. 6. Residual analysis of test one

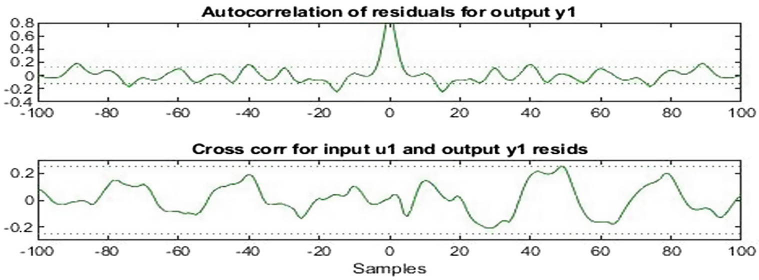


Fig. 7. Residual analysis of test two

$$\mu_P = \frac{\frac{1}{\epsilon_p(t)}}{\sum_{j=1}^{3} \frac{1}{\epsilon_j(t)}} \tag{4}$$

$$\sum\nolimits_{p=1}^{m} \mu_p = 1 \tag{5}$$

$$\mu_1 = 0.31199,\ \mu_2 = 0.3996,\ and\ \mu_3 = 0.28835$$

$$X(k+1) = \sum\nolimits_{P=1}^{m} \mu_P A_P X(k) + \sum\nolimits_{P=1}^{m} \mu_P B_P U(k) \tag{6}$$

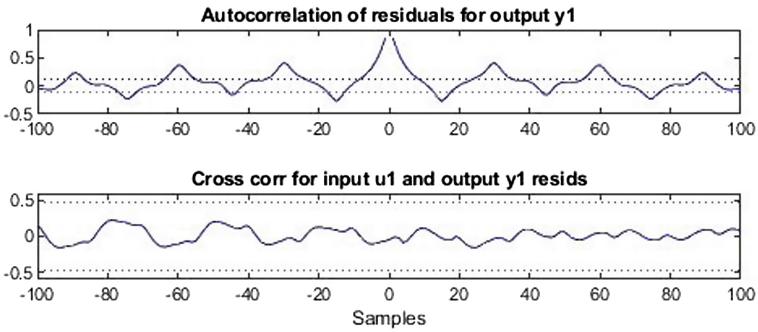


Fig. 8. Residual analysis of test three

Table 2. Transfer function model of shell and tube heat exchanger with different inputs

No	Plant model	Plant model best fit (%)	FPE	MSE
Test one	$G_1(s) = \frac{0.40696(1+47.22\,S)e^{-3.5S}}{10168.7\,S^2+965.78\,S+1}$	80.28	0.0115	0.01439
Test two	$G2(s) = \frac{0.21574(1+58.257\,S)e^{-3.15S}}{(1+475.55\,S)+(1+9.252\,S)}$	81.16	0.06881	0.06704
Test three	$G3(s) = \frac{0.13938(1+46.941\,S)e^{-2.82S}}{(1+452.47\,S)+(1+8.2768\,S)}$	80.86	0.1075	0.1048

Table 3. Transfer function of disturbance model

No of models	Disturbance model
Test one	$G_{d1}(s) = \frac{0.31407(1-27.057*S)e^{-6S}}{6441\,S^2+831.3\,S+1}$
Test two	$G_{d2}(s) = \frac{0.31089(1-87.816*S)e^{-7.5S}}{11238\,S^2+1690.6\,S+1}$
Test three	$G_{d3}(s) = \frac{0.29977(1-69.871*S)e^{-2.3S}}{11804.8\,S^2+1663.7\,S+1}$

$$Y(k) = \sum\nolimits_{P=1}^{3} \mu_P C_P X(k) \tag{7}$$

$$Y(k) = (\mu_1 C_1 X(k) + \mu_2 C_2 X(k) + \mu_3 C_3 X(k)) \tag{8}$$

The nonlinear system is approximated by the following global linear model.

$$X(k+1) = \begin{bmatrix} 0.9278 & -0.0271 & -0.0018 \\ 0.024 & 1 & 0 \\ 0 & 0.026 & 1 \end{bmatrix} X(k) + \begin{bmatrix} 0.0121 \\ 0 \\ 0 \end{bmatrix} U(k)$$

$$Y(k) = \begin{bmatrix} -0.0178 & 0.044 & 0.0351 \end{bmatrix} X(k) \tag{9}$$

The approximated linear model of shell and tube heat exchanger is shown as below equation.

$$G(s) = \frac{0.23601(1+49.8s)}{(1+9.625s)(1+567.9s)} e^{-3.252\,S} \tag{10}$$

The local linear disturbance models approximated to single global disturbance models.

$$G_d(s) = \frac{0.00013953\,(1+0.1772\mathrm{s})}{(1+0.1745\mathrm{s})(1+0.2342\mathrm{s})} \tag{11}$$

5 Conclusion

In this paper empirical model that represents the real system and handle unmolded disturbance and uncertainty is presented. Laboratory shell and tube heat exchanger has been used to conduct the experiment. Input-output data including the effect of disturbance was generated experimentally and fed to the MATLAB system identification toolbox as an input. To avoid system nonlinearities, the overall system is partitioned in to three operating range. For each particular operating range, input-output data has been collected and analyzed using MATLAB Software. Finally, after iterative procedure the partitioned plant models are obtained with satisfactory accuracy and residual values within range of limits. The results showed that the first test, the second test and the third test models have the best fit of 80.28% with MSE of 0.01439, 81.16% with MSE of 0.06704 and 80.86% with MSE of 0.1048 respectively. Finally, the overall model is approximated to single linear model that represent all operating ranges.

Acknowledgment. The Authors would like to acknowledge Department of Chemical Engineering of Addis Ababa Science and Technology University for their help during experimental setup.

References

1. Nithya, S., Gour, A.S., Sivakumaran, S., Radhakrishnan, T.K.: Predictive controller design for a shell and tube heat exchanger. In: IEEE International Conference on Intelligent and Advanced Systems, pp. 1075–1080 (2007)
2. Vasickaninova, A., Bakosova, M.: Robust controller design for a heat exchanger. In: IEEE International Conference on Process Control, pp. 113–118 (2016)
3. Tangirala, A.K.: Principles of System Identification Theory and Practice. CRC Press, New York (2015)
4. Vinaya, K.V., Ramkumar, K., Alagesan, V.: Control of heat exchangers using model predictive controller. In: IEEE International Conference Advance Engineering Science and Management, pp. 242–246 (2012)
5. Khan, S.: Modeling and Controlling Heat Exchanger Process. LAP Lambert Academic Publishing, Hamirpur (2017)
6. Thulukkanam, K.: Heat Exchanger Design Handbook. CRC Press, New York (2013)
7. Wayne, B.B.: Process Control Modeling, Design, and Simulation. Prentice Hall, Upper Saddle River (2002)
8. El Ferik, S., Ahmed, A.: Modeling and identification of nonlinear systems: a review of the multimodel approach—part 1. IEEE Trans. Syst. Man Cybern. Syst. **47**, 2168–2216 (2017)
9. Johansen, T., Bjarne, F.: Operating regime based process modeling and identification. In: Conference on Automatic Control, Trondheim, Norway, pp. 1–33 (1995)
10. Jingjing, D., Johansen, T.A.: Integrated multi-model control of nonlinear systems based on gap metric and stability margin. Ind. Eng. Chem. Res. **53**, 10206–10215 (2014)
11. El Ferik, S., Ahmed, A.: Modeling and identification of nonlinear systems: a review of the multi-model approach—part 2. IEEE Trans. Syst. Man Cybern. Syst. **47**, 2168–2216 (2017)
12. Palizban, H.A., Safavi, A.A., Romagnoli, J.A.: A nonlinear control design approach based on multi-linear models. In: Proceedings of the American Control Conference, New Mexico, pp. 3490–3494 (1997)

13. Nekoui, M.A., Sajadi, S.M.: Nonlinear system identification using locally linear model tree and particle swarm optimization. In: IEEE International Conference on Industrial Technology, Mumbai, pp. 1563–1568 (2006)
14. Imai, S., Yamamoto, T.: Design and experiment of a IMC-based PID controller using multiple local linear models. In: IEEE/ETFA International Conference on Emerging Technologies and Factory Automation, pp. 6505–6509 (2017)
15. Sivaram, A., Sainabha, M., Ramkumar, K.: Parameter identification and control of a shell and tube heat exchanger. Int. J. Eng. Technol. (IJET) **5**(2), 1589–1593 (2013)
16. Abdulrahman, A.A., Emhemed, A.A., Hanafi, D.: Modelling and controller design for temperature control of power plant heat exchanger. Univ. J. Control Autom. **5**(3), 49–53 (2017)
17. Mithun, P., Satheeshbabu, R., Thirunavukkarasu, I., George, V.I., Shreesha, C.: Non-linear controller design for shell and tube heat exchanger—an experimentation approach. In: Proceeding of 2nd The IRES International Conference, Berlin, pp. 31–35 (2015)