Heat Exchanger's Shell and Tube Modeling for Intelligent Control Design

Dirman Hanafi[1], Mohd Nor Mohd Than[2] , Abdulrahman A.A. Emhemed[3] ,Tatang Mulyana[4] , Amran Mohd Zaid[5] and Ayob Hj. Johari[6]
[1,2,3,4,5,6]Department of Mechatronic and Robotic Engineeering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
E-mail: dirman@uthm.edu.my

***Abstract-* The shell and tube of heat exchanger is a medium where heat transfer process occurred. The accuracy of the heat exchanger depends on the performance of both elements. Therefore, both components need to be controlled in order to achieve a substantial result in the process. For this purpose, the actual dynamics of both shell and tube of the heat exchanger is crucial. This paper discusses two methods used in deriving the mathematical modeling of the system. First, physical dynamic modeling is obtained using physics and dynamics laws where actual parameters of the shell and tube are considered. Secondly, the model is determined by applying non-parametric system identification based on experimental response on the heat exchanger. Two models are used to design the shell and tube intelligent control. The intelligent control type is a Fuzzy Proportional Derivative (FPD) control. The experiment results shows that the shell and tube heat exchanger model develop using its physical parameters and controlled with FPD controller give better response, it means it can used as a model and controller of the shell and tube heat exchanger.**

Keyword- Shell and tube, dynamic modeling, non-parametric modeling, intelligent control

I. INTRODUCTION

Nowadays heat exchanger widely used in industry like chemical process, oil and gas, nuclear plant, palm oil process, food, mechanical system and etc. Heat exchangers are used to transfer heat from one fluid to other [1]. The heat transferring reasons one of the following:

1. To heat cooler fluid by hotter fluid.
2. To reduce the temperature of hot fluid by cool fluid.
3. To boil a liquid by the hotter fluid.
4. To condense a gaseous fluid by a cooler fluid.
5. To boil a liquid while condensing a hotter gaseous fluid.

The heat transferring process is happen in shell and tube heat exchanger.

The process of the heat transfer two fluids with difference temperature in shell and tube heat exchanger are done without having surface contact. The output performance of a heat exchanger is greatly influenced by shell and tube. On the other hand, the demands of the process are not constant; the heat content of the two fluids is not constant either. Therefore, the shell and tube heat exchanger must be controlled to make it operate at the particular rate required by the process every moment in time.

In control system engineering, system investigation and improvement are done based on the system model. Therefore it is necessary to have a mathematical model of the given system. It must be a high fidelity mathematical model capturing realistic dynamic behaviors of the system [4]. The mathematical models describe the relationships among the system variables in terms of mathematical expressions like differential equations.

This paper is subject to improve the performance of the heat exchanger that it is installed in UTHM process control laboratory. In this case two modeling techniques and one type of intelligent control are applied.

The modeling techniques for shell and tube heat exchanger derives consisting of dynamic modeling that it has been applied physical and thermo dynamic laws [5]. In this research, the model parameters are calculated based on the real values of shell and tube heat exchanger components. Next modeling technique is system identification. The non-parametric system identification is applied. The heat exchanger model and its parameters are estimated using input output data of the heat exchanger that are collected in experimental testing [3,6].

Two models develop are used to design the shell and tube heat exchanger intelligent control. The intelligent control type is fuzzy control system [7,8]. To improve the fuzzy control performance in this case it combines with proportional derivative (PD) control as fuzzy proportional derivative (FPD) controller.

II. SHELL AND TUBE COMPONENT

There are several varieties of a shell and tube heat exchanger. The number of a basic component is relative small. Fig. 1 shows a shell and tube heat exchanger [2].

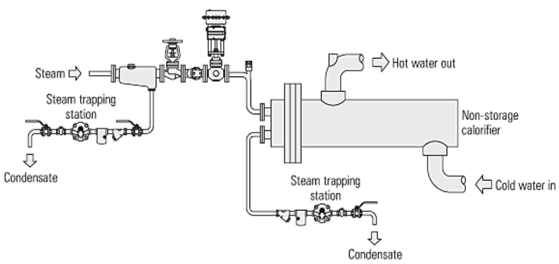

Figure 1. Shell and tube heat exchanger

The components consist of:

1. Tube: providing the heat transfer surface between one fluid flowing inside the tube and the other fluid flowing across the outside of the tubes.
2. Tube sheet: where the tube is held in place.
3. Shell and shell-side nozzles: container of the shell-side fluid and the inlet and exit ports.
4. Tube-side channels and nozzles: control the flow of tube-side fluid into and out of the tubes.
5. Channel covers: round the plates.
6. Pass divider: for two tubes side pass or more than two passes.
7. Baffles: support the tubes in the proper position and prevent vibration.

III. SHELL AND TUBE HEAT EXCHANGER MODELING

A. *Dynamic modeling of shell and tube heat exchanger based on physical parameters*

Mathematical model is a system model to represent the system dynamics in mathematic formulations [3]. This model is determined applying several physic and chemical laws and variables which are happening in process. Fig.2 shows several variables involve in shell and tube heat exchanger process.

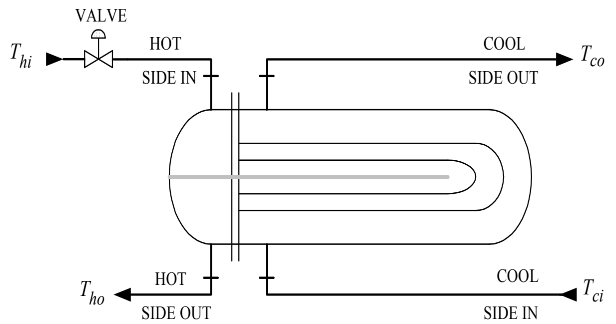

Figure 2. Shell and tube heat exchanger input output

Related to the energy balance law, the energy supply to heat exchanger must equal to the energy removed. This relationship is given by equation below:

$$\dot{T}_{co}(t) = w_c / \rho_c V_c (T_{ci}(t) - T_{co}(t)) + U_c A_c / \rho_c V_c C_{pc} (T_{ho}(t) - T_{co}(t)) \quad (1)$$

$$\dot{T}_{ho}(t) = w_h / \rho_h V_h (T_{hi}(t) - T_{ho}(t)) + U_h A_h / \rho_h V_h C_{ph} (T_{co}(t) - T_{ho}(t)) \quad (2)$$

Where, T_{ci}, T_{co}, T_{hi} and T_{ho} are inlet and outlet cold and hot fluid temperature (^oC) respectively. w_c and w_h are mass flow rate of cold and hot fluid ($kg/\sec$). C_{pc} and C_{ph} are the heat capacity of cold and hot fluid ($J/kg.^oC$). ρ_c and ρ_h are the density of cold and hot fluid (kg/cm^3). V_c, V_h, A_c, A_h, U_c and U_h are volume (cm^3), heat transfer surface area (cm^2), heat transfer coefficient ($W/cm^2\ ^oC$) cold and hot fluid respectively.

B. *Non-parametric system identification of shell and tube heat exchanger*

Non-parametric system identification is a technique to estimate the system model through its step response. The technique is based on two points of the fraction response of the system at 20% and 60% as shown by the following figure:

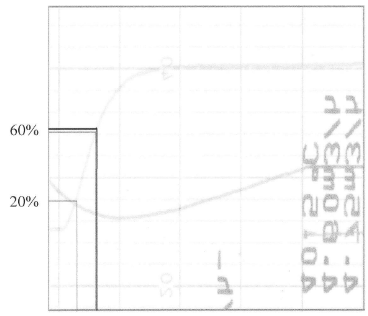

Figure 3. Real experimental the heat exchanger step response

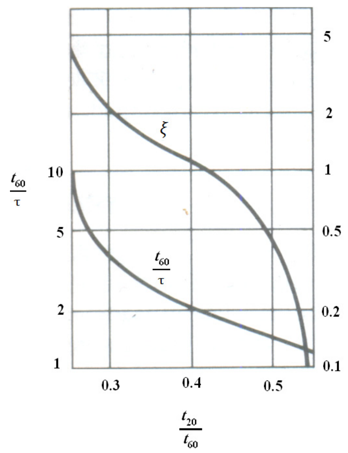

Figure 4. Smith 's chart

The value of damping ξ is equal to ratio of t_{20}/t_{60} and value of time delay τ determines from the graph of t_{60}/τ versus t_{20}/t_{60}. The transfer function of the system is given as:

$$G(S) = ke^{-t_0} / (\tau_1 S + 1)(\tau_2 S + 1) \quad (3)$$

Where $\tau_1 = \tau\xi + \sqrt{\xi^2 - 1}$ and $\tau_1 = \tau\xi - \sqrt{\xi^2 - 1}$, k is gain and t_o is time. After substitution the values need, the transfer function of shell and tube heat exchanger as below:

$$G(S) = 0.125/(23.3S)(2.46S+1)(0.0375+1) \quad (4)$$

IV. FUZZY CONTROL DESIGN FOR SHELL AND TUBE HEAT EXCHANGER

Fuzzy logic is based on the principle of human expert decision making in problem solving mechanism. Where, the solution is described in a linguistic term or every spoken language, i.e., fast, slow, high, low, etc [7,8]. In more complex cases, they include some hedge terms, i.e., very high, not so low, etc. To represent such terms, a nonmathematical fuzzy set theory is needed.

Fig. 5 shows the block diagram of fuzzy logic. They are consisted four components: Fuzzification, Fuzzy rule based, Fuzzy inference and Defuzzification.

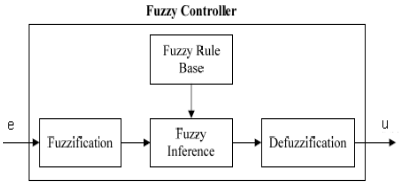

Figure 5. Fuzzy logic block diagram

The fuzzy logic controller for the quarter car passive suspension system is designed follow the step below:

1. Design the membership function for fuzzify input and output variables.
2. Implement the fuzzy inference by a series of IF – THEN rules.
3. Inference engine derives a conclusion from the facts and rules contained in the knowledge base using various human expert techniques.
4. Process to maps a fuzzy set into a crisp set.

Fuzzy logic control proposed in this research is design applying Matlab Fuzzy Logic Toolbox. The fuzzy inference system (FIS) is used to edit and visualize used rules and membership functions. The resulting FIS model is then tested using the Simulink Toolbox, which also gives the convenience of building and analyzing dynamical systems graphically.

Fuzzy proportional derivative (FPD) controller

Fuzzy proportional derivative (FPD) control developed is a multi input single output controller model. The inputs are error (E) and change in error (CE). Output is a signal control (U). Fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time [8]. Block diagram of FPD control that has been designed for shell and tube heat exchanger is represented by Fig. 6.

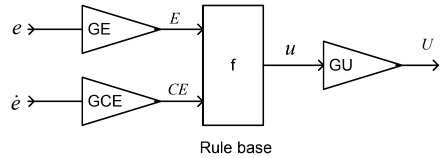

Figure 6. FPD controller block diagram

The shell and tube heat exchanger process dynamics take some time before a change in the control signal is noticeable in the process output, and the proportional controller will be more or less late in correcting for an error. Derivative action helps to predict the error and the proportional-derivative controller uses the derivative action to improve closed-loop stability. The basic structure of a PD controller is:

$$u(n) = K_p\left(e(n) + T_d\dot{e}(n)\right) \quad (5)$$

Notice that definition deviates from the straight difference ($e(n) - e(n-1)$) used in the early fuzzy controllers. The FPD controller output as function of error and change in error given as:

$$U(n) = f(GE * e(n) * GCE * \dot{e}(n)) * GU \quad (6)$$

Where function f denotes the rule base mapping. It is usually nonlinear, but with a favorable choice of design, a linear approximate is:

$$f(GE * e(n) * GCE * \dot{e}(n)) * GU \approx GE * e(n) + GCE * \dot{e}(n) \quad (7)$$

Then, the control signal becomes as below:

$$U(n) = GE * GU(e(n) + (GCE/GE)\dot{e}(n)) \quad (8)$$

The gain factor for the linear controller corresponds to the proportional and derivative gains are:

$$K_p = GE * GU \quad (9)$$

$$T_d = GCE/GE \quad (10)$$

The FPD controller is used to control the shell and tube heat exchanger valve. The linguistic terms for errors are: NE (negative error), ZE (zero error) and PE (positive error). Changes in errors are: NLDE (Negative Large Derivative Error), NSDE (Negative Small Derivative Error), ZDE (Zero Derivative Error), PSDE (Positive Small Derivative Error), PLDE (Positive Large Derivative Error). Outputs are: and for output are: u0 (valve 0-10), u25 (valve 0-25), u50 (valve 25-75), u75 (valve 50-100), u100 (valve 75-

100). The membership functions for input and output are assumed triangular type.

V. SIMULATION RESULTS

Simulation for FPD controller of the shell and tube heat exchanger is done using Matlab Simulink. The input signal is the cold fluid temperature shell and tube heat exchanger. Two models of shell and tube heat exchanger are controlled with FPD controller and the results are compared in order to decide which one produce good result. Each Matlab Simulink block control system related model are below:

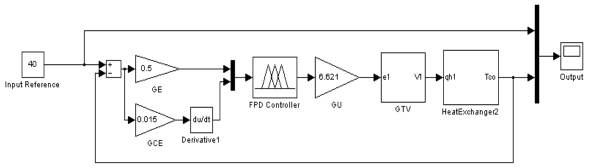

Figure 7. Matlab Simulink block control system for model from dynamic modeling

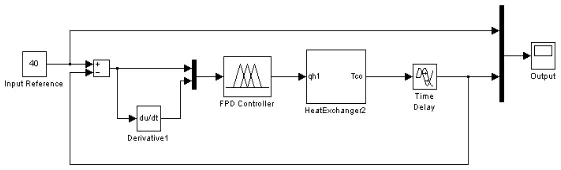

Figure 8. Matlab Simulink block control system for model from non-parametric system identification

Fig. 9 and 10 represent the response of each model to the input temperature. In this case the input value is assumed 40 degree Celsius. The two models responses have similar trend. While Fig. 11 shows the comparison between response of physical model and system identification model.

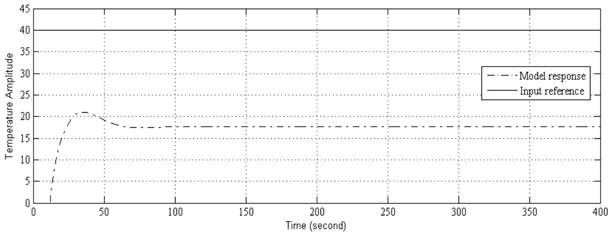

Figure 9. Response of physical model without controller

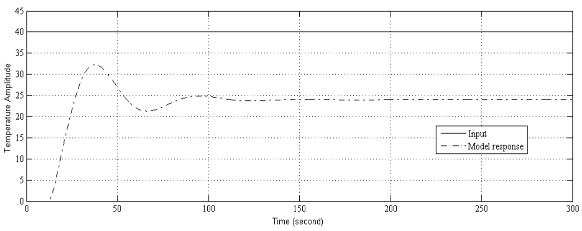

Figure 10. Response of system identification model without controller

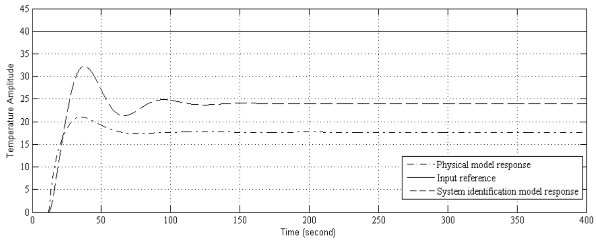

Figure 11. Comparison of two models response without controller

Fig. 12, 13 and 14 are the response of physical model, system identification model and comparison between two models response under FPD controller respectively.

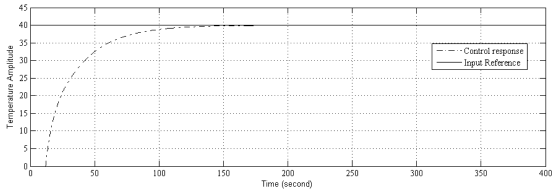

Figure 12. Response of physical model with FPD controller

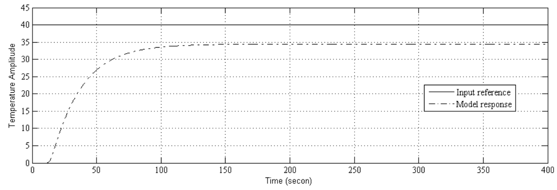

Figure 13. Response of system identification model with FPD controller

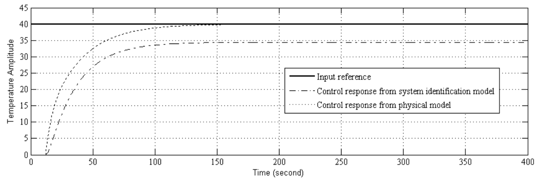

Figure 14. Comparison of two models response with FPD controller

Based on the comparison of models under FPD controller, the response of system identification model is not able to reach the input reference. It has steady sate error around 12.5%. While the response of physical model can reach model exactly at 150 second, no overshot, no steady state error and has settling time 80 second.

VI. CONCLUSION

In this paper, the shell and tube heat exchanger has been modeled and control using FPD Controller. The model that developed using shell and tube heat exchanger physical parameters has good response than the model that identified using non-parametric system identification. It means, the shell and tube heat exchanger model determined based on it physical parameter is feasible use to analysis and design it controller. And FPD controller also can apply to improve the shell and tube heat exchanger performance related with it successfully on the simulation.

ACKNOWLEDGMENTS

This work has been supported by Registrar Officer and Faculty of Electrical and Electronic Engineering Universiti Tun Hussein Onn Malaysia

REFERENCES

[1]. Engineer Edge, Heat Exchanger, LLC All right reserved, 2000. Spirax-sarco, Steam Consumption of Heat Exchangers, Spirax_Sarco Limited, 2010.

[2]. Y. Zhao, S. Zhou, and Li Li, "Dynamic Characteristics Modeling of a Heat Exchanger Using Neural Network", Proc. First International Conference on Intelligent Networks and Intelligent Systems, pp. 13-18, 1-3 November 2008.

[3]. Han-Shue Tan and T. Bradshaw, "Model Identification of an Automotive Hydraulic Active Suspension System," Proc. The American Control Conference, Vol. 5, pp. 2920-2924, 1997.

[4]. C. Harris, K. Kelly, T. Wang, A. McCandless and S. Motakef, "Fabrication, Modeling, and Testing of Micro-Cross Flow Heat Exchangers," Journal of Microelektromechanical Systems, Vol. 11(6), Dec. 2002, pp. 726-735.

[5]. I. Skrjanc and D. Matko, "Predictive Functional Control Based on Fuzzy Model for Heat-Exchanger Pilot Plant," IEEE Transaction on Fuzzy Systems, Vol 8(6), Dec. 2000, pp. 705-712.

[6]. D. Zhenjun, F. Lide, S. Zhambiao and Z. Yameng, "Design and Simulation of Fuzzy Control System for Water Temperature of Heat Exchanger," Proc. 2nd International Conference on Computer and Automation Engineering (ICCEA), Vol. 4, pp. 122-125, 26-28 Feb. 2010.

[7]. J. Jantzen, "Foundations of Fuzzy Control, John Wiley, 2007.

[8]. C. A and A. B. Corripio, Principles and Practice of Automation Process Control, 3rd Ed, Wiley, New York, 2006.