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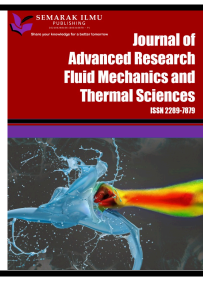

Evaluation of Interval Type-2 Fuzzy PID and Type-1 Fuzzy PID Controller Performance for Temperature System of Heat Exchanger

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ABSTRACT

The main control issue in a heat exchanger system is to regulate the outlet cold fluid temperature according to the setpoint. An appropriate control system is required in handling the heat exchange, whereby it involves the setpoint achievement of the system resulting in an excellent performance of the temperature control. In this paper, a comprehensive study regarding the standard PID controller and intelligent control such as Interval Type-2 Fuzzy inference system (IT2FIS) controller has been made. This study aims to develop a control system and to find the most effective optimization technique for the temperature control system of STHE. The comparison between controllers' performance based upon the transient response concerning the time domain specification has been carried out. As the findings from the data analysis, the IT2FIS controller is one of the effective control techniques in controlling the outlet temperature of cold water in STHE as an improvement to the FPID controller. From the transient response functionality, it is proven that the combination of IT2FIS and PID controller delivered a good output response with minimal overshoot, rise time, and settling time.

1. Introduction

There is a large volume of published studies describing the field of fuzzy logic, in fact, most of the models of fuzzy only focused on Type 1 FLC [1]. Despite Type 1 FLC popularity, scientific research has recently shown that in many cases Type 1 faces difficulties in minimizing the effect of uncertainties in the plant model, which are often responsible for the performance of process control [2]. Alternatively, this research designed and purposed the Type 2 FLC as fuzzy inference system in PID controller to control the outlet temperature of STHE plant which had uncertainties in the data measurement and changing environment. The goal of this controller is to achieve better transient

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and steady-state response characteristics compared with the previous FPID controller. Type 2 can help to deal with a higher level of uncertainty in a stable condition of world applications [3-4]. Though the major limitation of Type 2 FLC is its computational complexity, after all, it is quite robust to endure disturbances and parameter uncertainties compared to FPID controller [5].

Type 2 fuzzy set is an extension of Type 1 fuzzy set [6], which is introduced the third dimension to accommodate the uncertainty of the membership degree. It was introduced by Lotfi A.Zadeh in the 1975 [7]. Type 2 fuzzy sets and systems proven can better handle uncertainties compared to its Type 1 counterpart, and the widely applied support interval Type 2 fuzzy sets [8]. Moreover, the Type 1 fuzzy sets have limited ability to handle such uncertainties because Type 1 fuzzy sets applied crisp membership functions meanwhile the Type 2 fuzzy sets have a membership grade that is fuzzy itself. Because of this, the Type 2 FLC is very useful for applications to determine the exact membership function of a fuzzy set. Recently, studies on type-2 fuzzy logic systems have attracted growing attention because its ability to handle uncertainties [9]. These conditions ensure Type 2 FLC can perform better step response than Type 1 FLC as well as in handling the disturbances and setpoint changes [10].

2. Methodology
2.1 Experimental Setup

STHE plant consists of two phases, the heating phase and the cooling phase. This research focused on the heating phase as the aim of the research is to control the outlet fluid temperature of the STHE. The software used in this research work included MATLAB/Simulink 2020a, TIA Portal for SIEMENS, Programmable Logic Control (PLC), and Open Platform Communication (OPC) configuration and each of the software serve a specific purpose in the experiment. OPC, also known as Object Linking and Embedding (OLE) for process control is a software package that transfers data from field devices to the controller by using industrial communication methods. The OPC configuration is a client-based server that required OPC Server and OPC Client to communicate with each other. An OPC Server acts as data storage provides data i.e. name of devices, tagging, or access like reading or writing from PLC to an OPC Client application which is HMI. Figure 1 shows the software configuration applied along with this research.

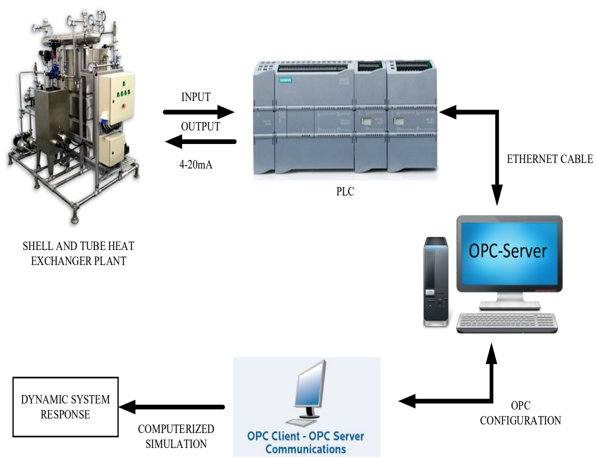


Fig. 1. Software configuration in STHE plant

In this research study, OPC is configured for all series experiments. Figure 2 shows the control commands, such as setpoint is set via OPC Write configuration while OPC Read configuration is used to read and log measurement from measuring devices such as temperature transmitter and flow transmitter. Conveniently, both OPC configurations provide connection to exchange data from/to PLC as well as user-interface (or HMI) for MATLAB-PLC real-time target.

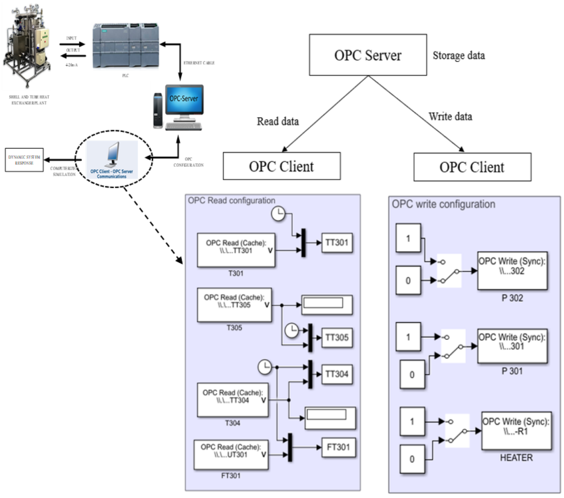


Fig. 2. OPC configuration based on STHE plant

2.2 Transfer Function Model

The open-loop experiments were carried out to determine the process characteristics in the implementation of the effective temperature controller for STHE. This is an important finding in the understanding of the analysis of process dynamic transfer function of STHE at a uniform temperature outlet tube side of heat exchanger by manipulating the inlet of hot fluid entering heat exchanger. Initially, the open-loop experiment presents the outlet temperature of cold fluid at steady state temperature 75° C. Significantly, this experimental study presents the estimation of the process model of STHE based on the process step response. Traditionally, a process characterized by step response of open-loop control system is modeled in practice by the equivalent FOPDT process model as explained earlier. From the open-loop test on heat exchanger plant, the experimental data collected via MATLAB generated as:

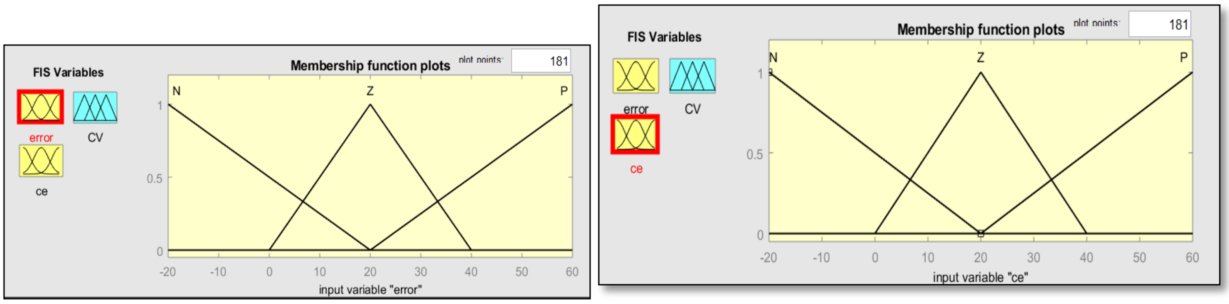
Process gain = 0.4718
Process time constant = 50.98s
Process time delay =19.47s.

The present study from the open-loop experiment confirmed the finding of the dynamic transfer function model for STHE plant in terms of FOPDT. The transfer function of control system STHE is concluded as:

〖0.4718e〗 s/(50.98s+1)

2.3 Fuzzy System Configuration

The stability of the control system with optimum system performance in terms of transient response with a fast response is a significant aspect in automatic temperature control systems like STHE. From the transient response of FPID controller, the performance can be further improved towards the robustness of the system operation. Therefore, the IT2 FLC was introduced in this research study to ensure the stability of the temperature control system by providing robustness in corresponding controllers for the STHE. The difference between Type 1 FLC and Type 2 FLC is Type 2 represented by the footprint of uncertainty (FOU) which is used to characterize a Type 2 fuzzy set. Type 2 FLC has a fuzzy membership function that modelling the imprecise nature behaviour of the system based on fuzzy membership grade.



(a) (b)

Fig. 3. Membership function of (a) inputs FPID controller for error (b) inputs of FPID controller for change of error

The two main categories of Type 2 FLC have emerged; (1) General Type 2 Fuzzy Logic Controller (GT2 FLC) and (2) Interval Type 2 Fuzzy Logic Controller (IT2 FLC). In this research work, the focus on IT FLC has been proposed to control the temperature of outlet fluid STHE by considering uncertainty in output produced. The comparison between Type 1 and Type 2 of fuzzy controller is done with respect to objective number three in the research study which is to compare the transient response performance of intelligent optimization techniques in temperature control system of STHE.

Figure 4 illustrates a general block diagram of IT2 FLC in temperature control system. Figure 5.19 represents the structure of control loop for IT2 FLC.

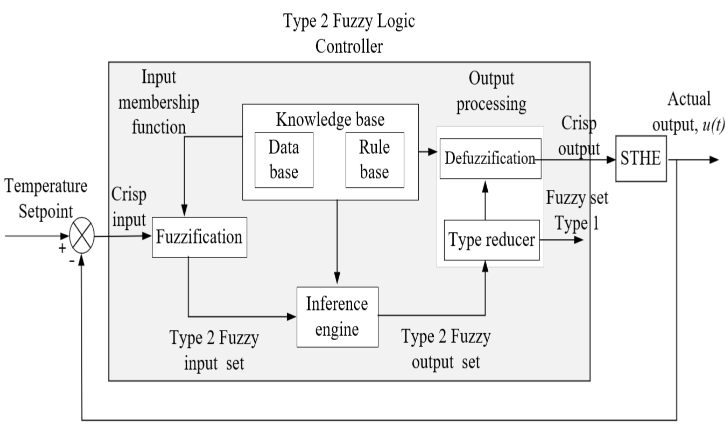


Fig. 4. Type 2 FLC in control system

The simulation experiments were done using Fuzzy Type 2 toolbox in MATLAB Software. The presented control system was devised based on the method of trial and error. Figure 5 shows the inputs and output relationship in IT2 FLC.

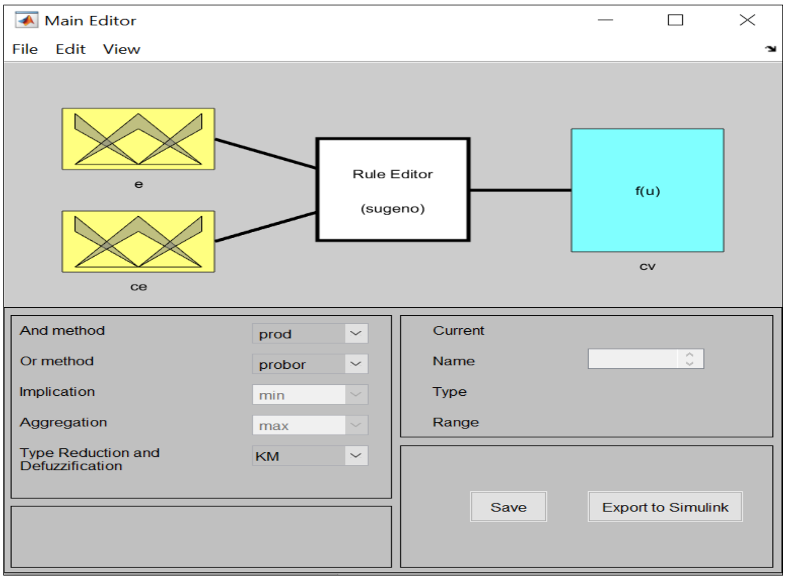


Fig. 5. Relationships between input and output of IT2 FLC

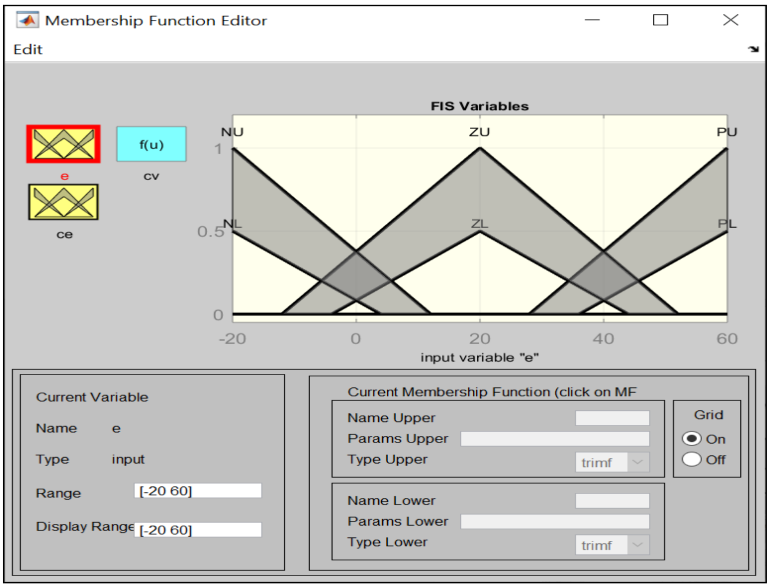


Fig. 6. Membership function for input of error for FPID controller

Figure 6 represents the control valve action as the output in this system. IT2 FLS rules remain same as Type1 FLC but the antecedents and/or consequents represent by IT2 fuzzy set. Figure 6 describes the IT2 FLC fuzzy rules applied in the simulation experiment.

3. Results

3.1 Transfer Function Model

The results of all the experiments based upon the real-time experiment and simulation test based on the transient response analysis generated using MATLAB/Simulink software 2020a. Another promising finding was to compare these optimization techniques between controllers including the fuzzy inferences system Type 1 and Interval Type 2 FLC with PID controller to increase the robustness of the control system. Considering all the collected data based upon the experimental and simulation study, the analysis of transient response performance concerning time domain specification and performance indices were discussed.

As multiple simulation experiments have been done along with this study, the comparison between conventional controllers and intelligent controllers gives clear views regarding the controller behaviors and performances. It can be seen that the temperature of the outlet fluid stabilized at the set point using the purpose controllers by taking the initial temperature of water at 30°C. Multiples setpoint were introduced to proof the robustness of the purposed controllers.

3.1.1 Controller Performance PID, Type-1 Fuzzy PID and Type-2 Fuzzy PID

The first comparison can be made between PID controller and FPID controller. The overshoot of PID controller is relatively large with oscillation being more intense whereby there is no overshoot appearing in the system performance when fuzzy inference systems were applied. In fact, the FPID controller transient response has better performance at the shortest settling time, faster response, and minimum overshoot. FPID controller gives the shorter time rise with 1.2s compared with PID controller about 32s. Moreover, the settling time of FPID was also reduced by 437s compared to PID controller about 477.5s. Here, it is proven that FPID controller has better control performance compared with the conventional PID controller in controlling the temperature outlet fluid of STHE. The simulation result also shows that the optimal tuning of PID using FLC significantly improves the set point tracking and the disturbance rejection and improves the system balance between the less initial energy used with faster response compared to PID controller. This experimental work proves that the tuning of a linear PID using fuzzy inference system Type 1 can be set as an optimization method since combining the FLC with PID control system enable a process to reach a predetermined set point.

However, in order towards the robustness of the temperature control system performance, the IT2 FLC-PID controller is implemented with the consideration of uncertainties and stability for the system operation. The fuzzy inference system of interval type 2 acts as the tuning method to the PID controller same as the previous FPID controller namely as IT2 FLC-PID controller. IT2 FLC-PID can automatically modulate parameters in real-time according to the derivation and the varying rate of deviations. MATLAB simulation results show that this IT2 FLC-PID can provide a better control effect than FPID. IT2 FLC-PID controllers can greatly improve the dynamic and stable performances of the systems. It is clearly showing that the IT2 FLC-PID has the smallest rise time value $78.87\times10^{(-3)}$ compared to FPID controller is 1.2s, and PID controller about 32s. From this time-domain specification, the IT2 FLC-PID controller also has the fastest response time compared to other controllers since the settling time is shortest from other controllers. From the results performance of these controllers, it shows that the IT2 FLC-PID controller is the best controller for the temperature control system of STHE.

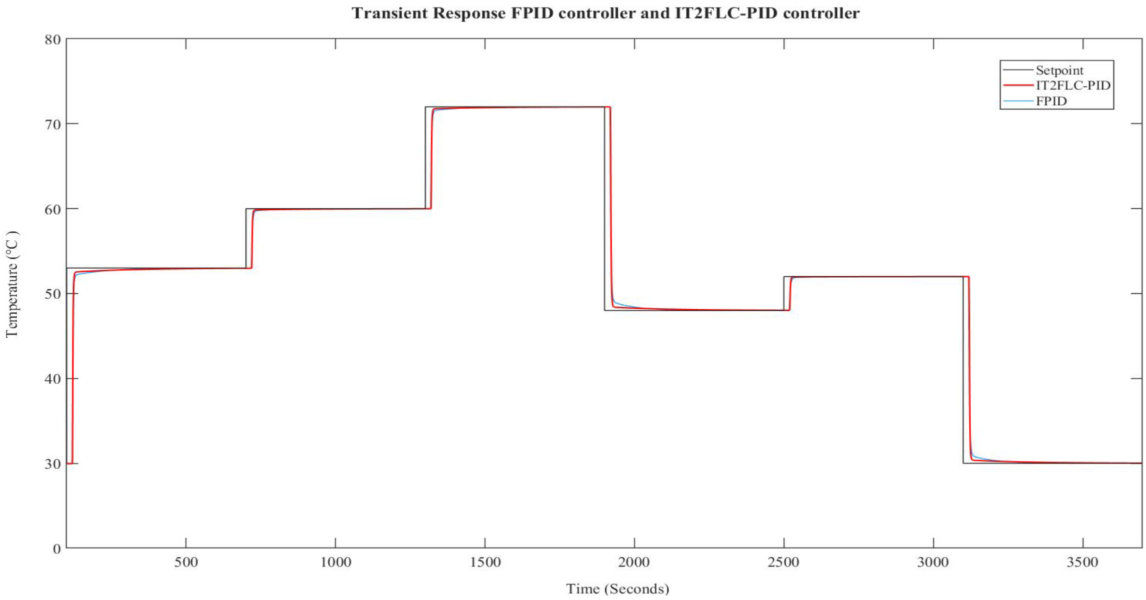


Fig. 7. Comparison of transient response conventional and intelligent controller

4. Conclusions

In this research study, the development of temperature control system for STHE using conventional PID closed-loop control was auto-tuned based upon the ZN tuning method, and the intelligent controller of fuzzy inference system of FLC and IT2 FLC were used as an added value for optimization of the PID gain namely as FPID controller and IT2 FLC-PID controller. For instance, the performance of IT2 FLC-PID controller was discussed by comparing the controller with PID controller and FPID controller. The analysis performance between all controllers is compared in terms of disturbances handling in controlling temperature. The analysis of all controllers was designed in MATLAB/Simulink.

In this study, the FPID has been introduced to overcome the drawbacks of conventional PID controller without considering uncertainties in output produce. This development is done to support the first objective of this research study which is to design robust intelligent controllers for STHE. The overall simulation results also proved that the FPID controller has better performance in terms of rise time with 1.2s compared to the conventional PID controller,32s.

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References
[1] K. A. Naik and C. P. Gupta, "Performance comparison of Type-1 and Type-2 fuzzy logic systems," in 2017 4th International Conference on Signal Processing, Computing and Control (ISPCC), 2017, pp. 72–76.
[2] M. Miccio and B. Cosenza, "Control of a distillation column by type-2 and type-1 fuzzy logic PID controllers," J. Process Control, vol. 24, no. 5, pp. 475–484, 2014.
[3] M. Galluzzo and B. Cosenza, "Control of a non-isothermal continuous stirred tank reactor by a feedback-feedforward structure using type-2 fuzzy logic controllers," Inf. Sci. (Ny)., vol. 181, no. 17, pp. 3535–3550, 2011.
[4] H. Hagras, Computational intelligent: Research frontiers, vol. 5050. 2008.
[5] R. R. De Maity, R. K. Mudi, and C. Dey, "Real-time evaluation of an interval type-2 fuzzy PID controller on servo position control system," Proc. 5th Int. Conf. Emerg. Appl. Inf. Technol. EAIT 2018, 2018.
[6] N. Altin, "Interval type-2 fuzzy logic controller based maximum power point tracking in photovoltaic systems," Adv. Electr. Comput. Eng., vol. 13, no. 3, pp. 65–70, 2013.

[7] M. Sajjad Ashfaq, “A Tribute to Father of Fuzzy Set Theory and Fuzzy Logic (Dr. Lotfi A. Zadeh),” Int. J. Swarm Intell. Evol. Comput., vol. 07, no. 02, 2018.
[8] J. Li, L. Yang, X. Fu, F. Chao, and Y. Qu, “Interval type-2 TSK+ fuzzy inference system,” IEEE Int. Conf. Fuzzy Syst., vol. 2018-July, 2018.
[9] N. Altin, “Interval type-2 fuzzy logic controller based maximum power point tracking in photovoltaic systems,” Adv. Electr. Comput. Eng., vol. 13, no. 3, pp. 65–70, 2013.
[10] M. Sajjad Ashfaq, “A Tribute to Father of Fuzzy Set Theory and Fuzzy Logic (Dr. Lotfi A. Zadeh),” Int. J. Swarm Intell. Evol. Comput., vol. 07, no. 02, 2018.