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Fuzzy Control Design for Energy Efficient Heat Exchanger Network

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Increasing energy efficiency and decreasing power consumption play a substantial role in the modern industrial and technological world. Consequently, there are enhanced requirements on all production processes and especially on energy intensive processes. Heat exchangers (HEs) and heat exchanger networks (HENs) are very energy intensive processes and only their optimal operation assures efficient heat recovery. Advanced optimization and advanced control are tools for assuring the energetic efficacy of HEs or HENs. Between them, fuzzy logic control represents the advanced control strategy that has many applications in industry and advantages as it can be used for control of strongly non-linear processes and processes that are difficult to control because of asymmetric dynamics or uncertainties. The type-1 and type-2 fuzzy logic controllers (FLCs) designed for a small heat exchanger network (HEN) are compared in this paper using simulation results with the PI and PID controllers tuned by conventional methods. The controlled HEN was a combination of two heat exchangers in series and one in parallel to them. The best controller was the type-2 fuzzy logic controller (FLC). This controller assured the most efficient operation of HEN measured by the smallest coolant consumption. The coolant consumption increased exploiting the type-1 FLC by 2 %, the PI controller by 3 %, and the PID controller by 5 %.

1. Introduction

In the modern industrial and technological world, where energy and its consumption represent the most important global interests, the demands on the sustainability of all production processes for the next generations are increasing. Klemeš et al. (2020) assessed recent developments in the field of improving heat transfer and modernizing heat exchanger networks and provided a critical analysis in terms of obtaining practical solutions. Saranya et al. (2017) dealt with modeling and control of plate, spiral, and shell and tube heat exchangers to achieve their more efficient control using integrated approaches. Kayabasi and Kurt (2018) derived economic calculations of parallel, countercurrent, cross flow, and other heat exchangers based on the relationships between efficiency and cost coefficients. Due to effectivennes and optimality, HEs are often combined into networks. Short et al. (2015) presented a new algorithm for the synthesis of HENs. The method combined two separate stages, namely the network topology optimization and the design stage that modeled the individual HEs.

Fuzzy logic control is often found in applications where conventional control does not assure satisfactory results because of non-linearity, asymmetric dynamics, and uncertainties in the controlled processes. Fuzzy logic is based on the theory of fuzzy sets introduced by Zadeh (1965). Fuzzy PID controllers may have many variants. Frequent versions are described by Pivoňka (2000). Shaheen et al. (2020) proposed a fuzzy controller for nonlinear systems with uncertainties. The controller combines the advantages of an adaptive Takagi-Sugeno-Kang fuzzy PID controller and probability theory. The concept of the type-2 fuzzy logic was introduced by Zadeh (1975). Mendel (2003) tried to motivate using the type-2 fuzzy sets. Tai et al. (2016) described the methods used to calculate the type-2 FLC outputs. Zhao and Xiao (2015) proposed a new interval type-2 fuzzy controller for the stabilization of nonlinear systems with parameter uncertainty. Begum and Marutheeswar (2015) used the type-2 FLC for temperature control of a double pipe heat exchanger system. Wati (2015) showed on air heater control that the type-2 fuzzy controller achieved better results

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compared to the type-1 FLC. Mendel (2018) covered rule-based systems from type-1 through interval type-2 to general type-2 fuzzy systems. Debnath et al. (2018) used a weighted interval type-2 fuzzy inference system for air quality assessment. Wu et al. (2019) assessed the performance of wind power coupling hydrogen storage projects from the perspective of sustainability using the interval type-2 fuzzy technique. As a part of future application work, new applications in the real world will be explored, e.g. hardware implementations, applications in medical diagnostics, big data, applications in robotics (Mittal et al., 2020).

Despite intensive research and promising applications in various fields, there is a lack of publications devoted to the implementation of the type-1 and type-2 FLCs to HENs. The main goal of this paper is to show that fuzzy controllers and especially the type-2 FLCs can guarantee energy savings and better performance compared to conventional PID controllers when controlling a small HEN. The presented comparative study of the type-1 FLC, type-2 FLC, PI controller, and PID controller is based on simulation results.

2. Fuzzy control

2.1 Type-1 fuzzy control

The design of a simple type-1 fuzzy controller (Figure 1) can be based on a procedure that is built on PID control. The algorithm is as follows: start with a PID controller, insert an equivalent linear fuzzy controller, and make it gradually nonlinear. A fuzzy controller can include empirical rules that are called a rule base. A dynamic controller would have additional inputs, for example, derivatives, integrals, or previous values of measurements backward in time. The block fuzzification converts each piece of input data to degrees of membership by a lookup in one or several membership functions. The rules may use several variables, both in the condition and the conclusion of the rules.

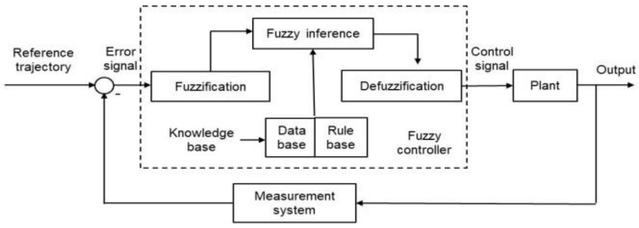

Figure 1: Feedback control structure with a type-1 fuzzy controller

Basically, a linguistic controller contains rules in the if-then format, but it can be presented in different formats. The resulting fuzzy set must be converted to a number that can be sent to the process as a control signal. This operation is called defuzzification. There are several defuzzification methods. Output scaling is also relevant. In the case the output is defined on a standard universe, it must be scaled to engineering units.

2.2 Interval type-2 fuzzy control

The rule base for the interval type-2 fuzzy controller (Figure 2) remains the same as for the type-1 FLC, but its membership functions are represented by type-2 interval fuzzy sets instead of type-1 fuzzy sets and some type of reducer is used prior defuzzification (Kumbasar, 2014).

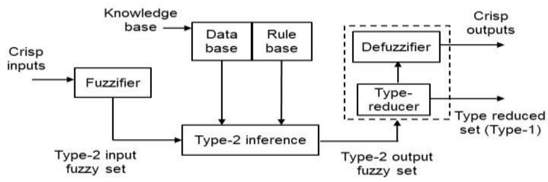

Figure 2: Interval type-2 fuzzy controller block diagram

The advantage of using type-2 fuzzy logic over type-1 is that type-2 can handle the inherent uncertainty in control, which can be due to noise, dynamic changes in the environment, or imprecision in the models (Mittal et al., 2020).

3. Process description and control design

The investigated HEN composed of two HEs in series parallel to one HE is presented in Figure 3.

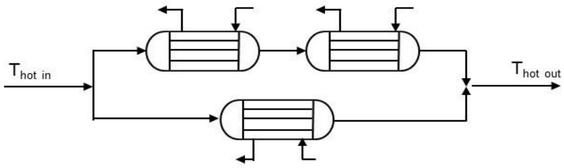

Figure 3: Scheme of the heat exchanger network

Kerosene flows in the inner tubes. Water is used as a cooling fluid and it flows in the shell of each heat exchanger. The objective is to decrease the kerosene temperature $T_{hot\,out}$ in the mixed outlet stream. The manipulated variable is the coolant flow rate. The simplified nonlinear dynamic mathematical model of the HEs has the form of six first-order ordinary differential equations (Oravec et al., 2016). Parameters and steady-state inputs of the HEs are given in Vasičkaninová et al. (2017).

3.1 Identification of the heat exchanger network

The explored HEN (Figure 3) was identified using the Strejc method (Mikleš and Fikar, 2007) in the form of a second order transfer function with a time delay Eq(1), where *s* represents the Laplace transform argument. The process model in Eq(1) was needed for PI and PID controller tuning. As several step responses were identified, intervals were obtained for the gain *K*, the time delay *D* and the time constant τ. The nominal values of the parameters are the mean values. The resulting nominal values of the transfer function parameters are K_{mean} = – 50.1 °C min m^{-3}, τ_{mean} = 1.8 min and D_{mean} = 0.1 min and the order is n = 2.

$$S = \frac{K}{(\tau s+1)^n}\mathrm{e}^{-Ds} = \frac{-50.1}{3.24\,s^2+3.6s+1}\mathrm{e}^{-0.1s} \tag{1}$$

3.2 Conventional PID control of the heat exchanger network

The nominal plant model Eq(1) was used to design the parameters of PID and PI controllers. The PID controller was tuned using the Chien-Hrones-Reswick method and PI controller was tuned using minimum ITAE method (Corriou, 2004). The transfer function of the PID controller *C* with a filtered derivative part was considered in the form:

$$C = k_p\left(1+\frac{1}{t_i s}+\frac{t_d s}{\frac{t_d s}{N}+1}\right) \tag{2}$$

where k_p is the proportional gain, t_i the integral time, t_d the derivative time and *N* is a constant. The PID controller parameters are presented in Table 1 and *N* = 20. The negative value of the controller gain k_p expresses the fact that the higher cooling agent flow rate is applied, the lower temperature of the outlet stream $T_{hot\,out}$ is reached.

Table 1: Parameters of the conventionally tuned PID and PI controllers

Controller	k_p (m^3 min^{-1} °C^{-1})	t_i (min^{-1})	t_d (min)
PID Chien-Hrones-Reswick	–0.3413	2.52	0.047
PI minimum ITAE method	–0.1565	1.56	0

3.3 Fuzzy control of the heat exchanger network

The type-1 fuzzy controller was designed as the Sugeno-type fuzzy inference system (FIS) in Eq(3),

$$\begin{aligned}
&\text{If } e \text{ is } A_1 \text{ and } de/dt \text{ is } B_1 \text{ Then } f_1 = p_1 e + q_1\, de/dt + r_1\\
&\text{If } e \text{ is } A_1 \text{ and } de/dt \text{ is } B_2 \text{ Then } f_2 = p_2 e + q_2\, de/dt + r_2\\
&\text{If } e \text{ is } A_2 \text{ and } de/dt \text{ is } B_1 \text{ Then } f_3 = p_3 e + q_3\, de/dt + r_3\\
&\text{If } e \text{ is } A_2 \text{ and } de/dt \text{ is } B_2 \text{ Then } f_4 = p_4 e + q_4\, de/dt + r_4\\
&\text{If } e \text{ is } A_3 \text{ and } de/dt \text{ is } B_1 \text{ Then } f_5 = p_5 e + q_5\, de/dt + r_5\\
&\text{If } e \text{ is } A_1 \text{ and } de/dt \text{ is } B_3 \text{ Then } f_6 = p_6 e + q_6\, de/dt + r_6
\end{aligned} \tag{3}$$

where e is the control error, de/dt is the derivative of error, p_i, q_i, r_i are the consequent parameters. Sugeno-type FIS was generated using a subtractive clustering method. The symmetric Gaussian function was used for the fuzzification of inputs. Figure 4 shows three Gaussian membership functions for the input e and two membership functions for the input de/dt. Figure 4 also shows three input interval type-2 fuzzy sets for the input e and two interval type-2 fuzzy sets for the input de/dt (Wu and Mendel, 2009). An interval type-2 membership function is represented by an upper and a lower membership function. The area enclosed by these membership functions is the footprint of uncertainty. The type-2 reducer uses the Karnik-Mendel algorithm (Karnik and Mendel, 2001).

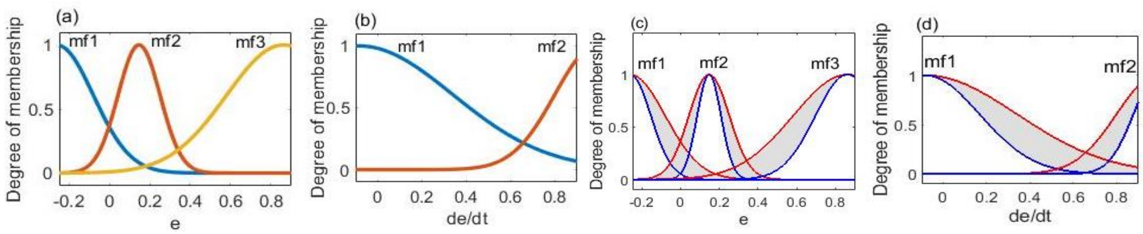

Figure 4: Gaussian membership functions: (a) – input e, (b) - input de/dt; interval type-2 membership functions: (c) – input e, (d) – input de/dt

4. Simulation results

The simulation results were attained using the MATLAB/Simulink R2020b programming environment. The Control and Fuzzy toolboxes were used for the implementation of PID and fuzzy controllers. The simulation results in reference tracking and disturbance rejection with measurement noise are presented in Figure 5. The reference temperature r = 80 °C was set at time t = 0 min and changed to 77 °C at t = 60 min. The disturbances were represented by the coolant temperature changes in the inlet stream to the HEN and they were as follows: the temperature increased by 4 °C at t = 30 min and decreased by 3 °C at t = 90 min.

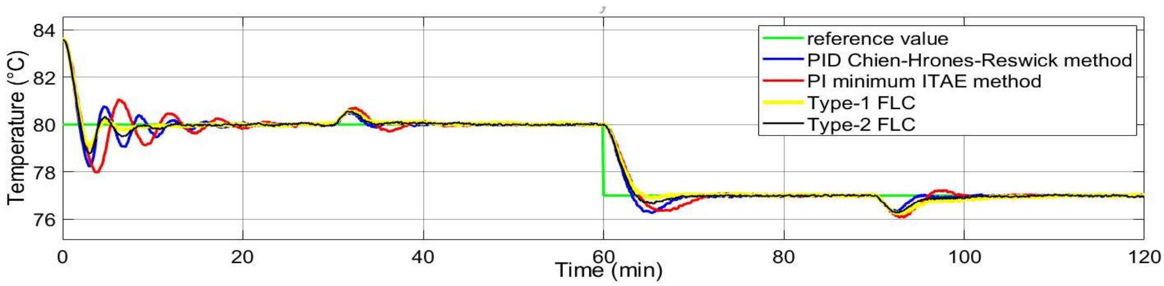

Figure 5: Control responses of the kerosene temperature $T_{hot\ out}$

The results were compared numerically assessing the total consumption of cooling water V consumed during control, the integral quality criteria IAE (integrated absolute error), and ISE (integrated squared error) defined e. g. in Corriou (2004). Table 2 summarizes these numerical results.

Table 2: Values of V, ISE, IAE

Controller	V (m^3)	ISE (°C^2 min)	IAE (°C min)
PID Chien-Hrones-Reswick	78.81	30.2	23.1
PI minimum ITAE method	77.22	41.8	31.8
Type-1 FLC	76.28	28.2	21.1
Type-2 FLC	75.01	27.6	20.2

The type-2 FLC (FLC2) guaranteed the lowest coolant consumption with 5 % reduction in comparison with the highest consumption reached by the PID controller. The type-1 FLC (FLC1) increased the coolant consumption by 2 % compared to FLC2. Evaluating the ISE and IAE values, the best controller was FLC2. FLC1 increased the ISE value by 2 % and the IAE value by 4 % compared to FLC2. The ISE value increased by 51 % and the IAE value by 57 % when the PI controller was used. Exploiting the PID controller, the ISE

value increased by 9 % and the IAE value by 14 %. Comparing the coolant consumption and the ISE and IAE values, FLC2 was the best controller.
The maximum overshoots and settling times were evaluated for the setpoint changes at t = 0 min (case 1 (C1)) and at t = 60 min (case 3 (C3)) and also for loaded disturbances at t = 30 min (case 2 (C2)) and at t = 90 min (case 4 (C4)). Overshoot percentage measures the closeness of the response to the desired response. The settling time is the time taken for the system to converge to its steady state (Skogestad, 2003). Table 3 and Table 4 contain these numerical results.

Table 3: Values of overshoots and settling times in setpoint tracking

Controller	Overshoot (C1) (%)	Settling Time (C1) (min)	Overshoot (C3) (%)	Settling Time (C3) (min)
PID Chien-Hrones-Reswick	49.48	17.4	13.55	42
PI minimum ITAE method	56.46	24.1	21.17	42
Type-1 FLC	25.41	12.3	14.12	38
Type-2 FLC	34.72	12.3	14.68	38

Table 4: Values of overshoots and settling times in disturbance rejection

Controller	Overshoot (C2) (%)	Settling Time (C2) (min)	Overshoot (C4) (%)	Settling Time (C4) (min)
PID Chien-Hrones-Reswick	24.10	70	20.67	100
PI minimum ITAE method	22.67	72	31.67	104
Type-1 FLC	3.00	64	25.00	105
Type-2 FLC	10.01	68	23.33	102

In setpoint tracking, FLC1 compared to FLC2 decreased the overshoots by 27 % (C1) and by 4 % (C3). The settling times were the same using both FLCs. The worst results were achieved by the PI controller. In comparison with FLC2, the overshoots increased by 63 % (C1) and by 44 % (C3) and the settling times increased by 96 % (C1) and by 11 % (C3). In disturbance rejection, FLC1 compared to FLC2 decreased the overshoot by 70 % and the settling time by 6 % in C2 but increased the overshoot by 7 % and the settling time by 3 % in C3. The worst results were achieved again using the PI controller. In comparison with FLC2, the overshoots increased by 126 % (C2) and by 36 % (C4) and the settling times increased by 6 % (C2) and by 2 % (C4). PID controller guaranteed the best control performance according to the overshoots when the setpoint and the disturbance decreased (C3 and C4). Comparing the overshoots and settling times, the best controller was FLC1.

5. Conclusions

Fuzzy control of a small HEN was studied. The type-1 FLC, type-2 FLC, and conventional PID and PI controllers were used for temperature control of the HEN. The type-2 FLC assured the most efficient operation of HEN measured by the lowest coolant consumption. The consumption of cooling agent increased by 2 % using FLC1, by 3 % using the PI controller, and by 5 % using the PID controller. Based on the maximum overshoots and settling times evaluated for the setpoint changes and loaded disturbances, the best results were obtained using FLC1 followed by FLC2. Judging the settling times in setpoint tracking, FLC1 reached the same results as FLC2 in C1 and C3 and compared to FLC2 decreased the settling time by 6 % in C2 and increased the settling time by 3 % in C4. The worst results were reached exploiting PI controller tuned by the minimum ITAE method and in comparison with FLC2, the settling times increased from 2 % (C4) to 96 % (C1). Evaluating the overshoots, FLC1 assured the smallest overshoots in C1 and C2, and these overshoots were 25.41 % and 3.00 %. In C3 and C4, the best controller was the PID controller with overshoots of 13.55 % and 20.67 % followed by FLC1 with the overshoot of 14.12 % in C3 and by FLC2 with the overshoot of 23.33 % in C4. Based on the comparison of all results, it can be stated that both types of FLCs could be used successfully for reaching the goals of control. Application of more complicated fuzzy type-2 controllers helped to improve the energetic efficiency of the studied heat exchanger network measured by coolant consumption. This strategy is promising for implementation in practice. Further research in this field will continue in the future.

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