Proposal of a Fuzzy Control System for Heat Transfer Using PLC

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Abstract. The article presents a fuzzy controller design for using PLC as a control system. The subject of controlling is a mathematical model of a heat exchanger modeled in Simulink. The control algorithm was developed and configurated in the FuzzyControl++ configuration tools for the automation of technical processes. The goal of the paper is to explore the possibilities to implement and realize the potential of fuzzy control in areas belonging to the domain of classical regulation. Model of the closed loop control system in virtual environment is used to perform multiple simulations to detect the system behavior under various conditions. It is concluded that the applied control strategies can offer same properties in progress of regulation and offer better approach to intuitive knowledge base design and configuration parameters of controller.

Keywords: Fuzzy control · Programmable logic controller · Heat exchange

1 Introduction

Efficient control is tightly related to improvements in the quality of industrial production processes. In complex plants, a choice has to be made between the various available strategies (conventional, fuzzy and neural) developed in last decades. In the industry, fuzzy logic is implemented in non-linear closed-loop controllers, response prognostics of mathematically complex processes or a process automation application that cannot be solved with existing standard tools. Empirical process know-how and verbalized knowledge by experience can be directly transformed into controllers, patter identification or decision logic. Numerous intuitive software programs, which require only minimal specialist knowledge about fuzzy logic, allows to use fuzzy logic in many fields and applications of industrial automation.

The model of an indirect heat exchanger and a Fuzzy control system is designed in this paper. For the designing process of the exchanger model, Matlab Simulink was used. Simulink is widely used to spread engineering ideas, including developing safety-critical software [1], designing industrial communication

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systems [2], designing controllers for various systems [3,4], and others. Fuzzy Logic Toolbox software provides the direct implementation of the control system into a simulation as in [5]. Nowadays, many processes operated by humans are automated using various control techniques. Conventional control technique performance, such as PID control, in itself is often inferior to that of the human operator. One of the reasons is that linear controllers, which are commonly used in conventional control, are not appropriate for nonlinear plants. Another reason is that humans aggregate various kinds of information and combine control strategies, that cannot be integrated into a single analytic control law.

Fuzzy logic can capture the continuous nature of human decision processes and as such is a definite improvement over methods based on binary logic (widely used in industrial controllers). Programmable Logic Controller systems were used typical for discrete (event) control – automotive, electronics, etc. Their primary goal was to replace the relay technology. Nowadays, wide instruction libraries including function block for continues control (well-designed PID, lead-lag blocks, etc.) together with fuzzy toolboxes for PLCs and a universal fuzzy system for PLC with a possibility to convert Matlab fuzzy system into PLC's fuzzy structure do exist [6].

2 Materials and Methods

In this paper, mathematical model of controlled system represent heat transfer in indirect heat exchanger. The model is based on template system presented in [7]. The heat exchanger consist of two tanks. The tanks shares one wall as a partition. This partition is used for heat transfer and has surface area S. Warmer liquid A is in the first tank, with input temperature T_1 and output temperature T_{10}. Colder liquid B is in the second tank, with input temperature T_2 and output temperature T_{20}. In the system is a flow valve, which regulates the flow of the liquid A into the first tank (Fig. 1).

In the considered system, q_1 denotes the amount of the fluid A in-flowing to the first tank with volume of V_1. The fluid B in-flows to the second tank with the amount of q_2. The second tank has volume V_2. The changes of temperatures of fluids in the tanks are expressed by the equation

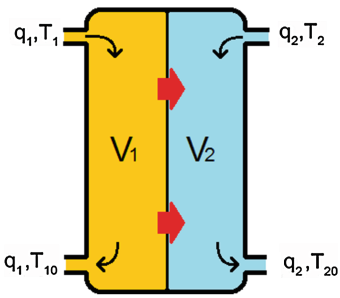

Fig. 1. Indirect heat exchanger

$$\frac{dT_{10}}{dt} = \frac{q_1}{V_1}T_1 - \frac{q_{10}}{V_1}T_{10} - \frac{k_s S}{\rho_1 c_{p1} V_1}(T_{10} - T_{20}), \quad (1)$$

$$\frac{dT_{20}}{dt} = \frac{q_2}{V_2}T_2 - \frac{q_{20}}{V_2}T_{20} + \frac{k_s S}{\rho_2 c_{p2} V_2}(T_{10} - T_{20}), \quad (2)$$

where k_s is thermal conductivity of partition, ρ is density of liquids and c_p is specific heat capacity of liquid. From these formulas, following block diagram was composed (Fig. 2). To build the model in Matlab Simulink it was necessary to take into account the adjustable input amount of the fluid q_1 using the input flow valve (Fig. 3). Controlling of the temperature of the fluid B in the second tank is made by adjusting q_1, the inflow of fluid A to the first tank. Blocks Divide modules were added to the block diagram, which enable setting input flow q_1 using the fuzzy controller. The required information about characteristics of the system was obtained from the modified model. The information was used to correct the design of the fuzzy controller.

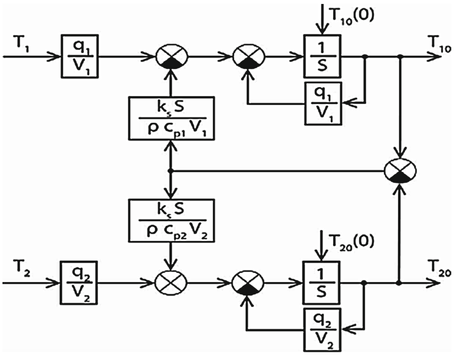

Fig. 2. Block diagram of indirect heat exchanger

All parts of closed loop control system can be designed in Simulink, but it is possible to send some data out of the Simulink model for calculations. Figure 4 shows the model of controller. The error signal e and the change of the error de are obtained, their values are converted and then sent to the PLC. The PLC uses fuzzy logic to calculate the control signal u, which is send back to the Simulink. To imitate system with flow valve as a regulator, Limited Integrator was added as a subsystem (Fig. 5) where the function $f(u)$ is as follows:

$$f(u): \; u[2] \times (((u[1] > 0) + (u[2] >= 0)) > 0) \times (((u[1] < 1) + (u[2] <= 0)) > 0) \quad (3)$$

Proposal and testing the fuzzy control of the heat exchanger was carried out in Matlab Simulink. PLC systems is now used to implement the fuzzy logic in the control process. It is possible to implement fuzzy logic and fuzzy control

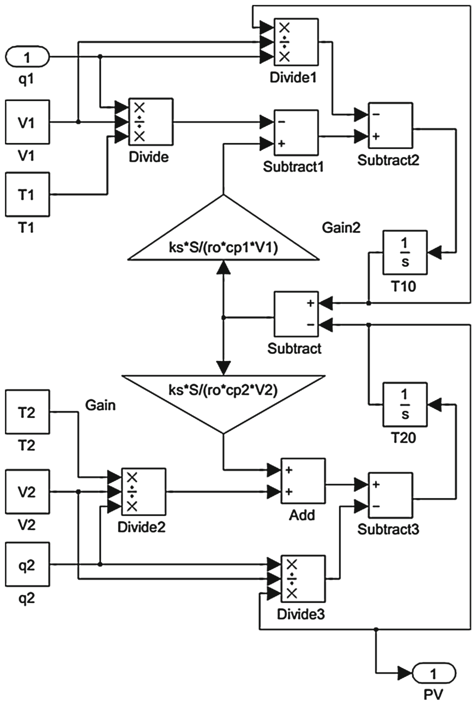

Fig. 3. Matlab model of indirect heat exchanger

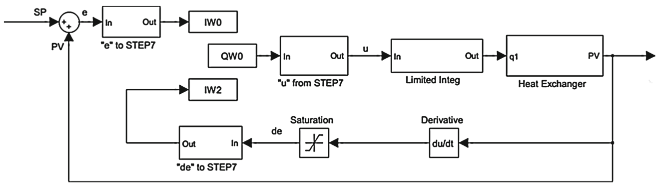

Fig. 4. Feedback control loop

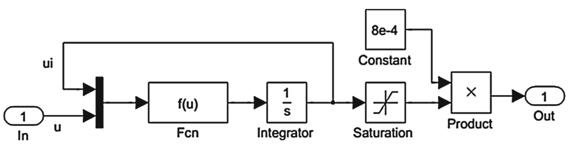

Fig. 5. Limited integrator

in industrial controllers with FuzzyControl++, a Siemens configuration tool. Development and configuration of fuzzy system is divided into two steps. In first step, the model of control system is modified in FuzzyControl++. In second step, created data are downloaded to the PLC and the parameters are adjusted more precisely. Developing and testing of the PLC fuzzy controller was carried on in the virtual SIEMENS PLC S7-300. The processor was CPU315F-2 and MPI interface was used to communicate with FuzzyControl++. Real-time connection between Matlab Simulink and the PLC program was provided by the PLCSIM blockset. In the PLC, the function block FB30 contains all the fuzzy algorithms and procedures. The program automatically creates the data block DB30. This data block contains all the variables and the parameters which represent the structure of the fuzzy controller. The function block contains also the memory elements, which are required to call function block FB30. It was necessary to take into account, that if the Simulink model of heat exchanger uses data type of INTEGER, the input and output from function block FB30 is only data type of REAL. Therefore, conversion of input and output values are required in PLC program. The fuzzy controller was proposed as a Sugeno type and was designed in the FuzzyControl++.

This controller has two inputs (error signal e and derivation of the error signal de), and it has one output signal (the control signal u). Both of the input signals e and de are defined by three membership functions. More functions does not improve the accuracy of control but proportionally increase the computation time. The functions were drafted in Membership Function editor using a Gaussian curve for each input signal. The error signal e was in the interval from $-20°$ C to $20°$ C (Fig. 6) and the change of the error de was in the interval from $-0.1°$ C to $0.1°$ C (Fig. 7). The control signal u is output from designed fuzzy module and this output signal is characterized by five membership functions *close_full, close_more, without_change, open_more, open_full.* The function *close_full* fully closes the flow control valve and the function *open_full* fully opens the valve. The functions *close_more* and *open_more* control the valve setting in small steps. The function *whitout_change* makes no change on valve setting. Features of controller also follows from fuzzy rules. Proper reaction of controller is dependent on the appropriate design of fuzzy rules. The rules are created and

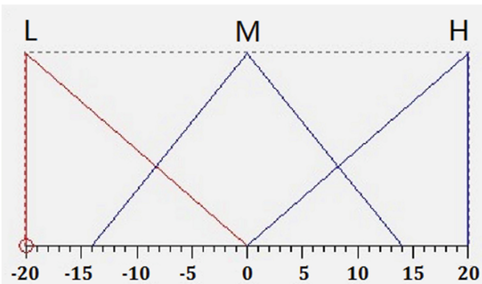

Fig. 6. Input variable "e"

Fig. 7. Input variable “de”

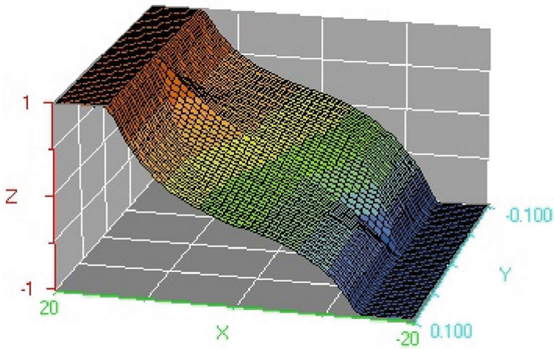

Fig. 8. 3D representation of fuzzy rules

edited in the editor of fuzzy rules. The fuzzy rules for calculating the value of the control signal u are as follows (Fig. 8):

- If (e is M) and (de is Z) then (u is *whitout_change*)
- If (e is M) and (de is P) then (u is *close_more*)
- If (e is M) and (de is N) then (u is *open_more*)
- If (e is L) then (u is *close_full*)
- If (e is H) then (u is *open_full*)

3 Results and Discussion

Sugeno fuzzy controller has been tested in several stages. At the beginning, proposed design of controller has to be tested. During this test, the control process was not affected by any error from outside and set point was static in time. The result of this test was correct response of the control signal to difference between set point and actual value of the output temperature of the liquid B. If the desired and the actual temperature were equal, then the control signal stays in its stabilized value. If the difference between the desired and the actual temperature were positive or negative then the control signal was decreasing or increasing. If the actual temperature was in the appropriate proximity of the set point then dynamical characterization was taken into consideration. Whether change of the actual temperature was positive or negative, the control signal was increasing or decreasing.

The next stage involved testing in closed loop controlling of heat transfer. Initial condition of model parameter was set according the Table 1. Dynamical characterization of the actual temperature of the fluid B and desired temperature as a set point were compared. If controller failed in expected demands, then parameters of membership function were adjusted. Several simulations with constant values of a set point were performed and the progress of process variable was monitored.

Table 1. Input parameters of the system

Symbolic name	Initial value	Description
ρ	$1000\,\mathrm{kg/m^3}$	Density of liquids
k_s	$1000\,\mathrm{Wm^2/K}$	Thermal conductivity of partition
V_1	$0.03\,\mathrm{m^3}$	Volume of the 1st tank
V_1	$0.04\,\mathrm{m^3}$	Volume of the 2nd tank
S	$2\,\mathrm{m^2}$	Surface area of partition
c_{p1}	$4195\,\mathrm{kJ/(kg\ K)}$	Specific heat capacity of liquid A
c_{p2}	$4183\,\mathrm{kJ/(kg\ K)}$	Specific heat capacity of liquid B
q_1	$0.0001\,\mathrm{m^3/s}$	Rate of flow of liquid A
q_2	$0.00021\,\mathrm{m^3/s}$	Rate of flow of liquid B
T_1	$80°$ C	Input temperature of liquid A
T_{10}	$80°$ C	Output temperature of liquid A
T_2	$20°$ C	Input temperature of liquid B
T_{20}	$20°$ C	Output temperature of liquid B

After fulfilling all requirements, the system was tested using a variable value for set point instead of constant value. In the model this signal was generated by the Signal Builder block. The signal was changing in steps and reaction of the fuzzy controller was monitored. Ability of system reaction in time shows Fig. 10. The test started with initial set temperature of 30° C.

At the beginning, the desired temperature was 30° C. Overshoot appeared but it did not indicate the wrong functionality of the controller in this case. The transfer heat between liquids takes some time, so the controller responses to temperature changes gradually. Because of the inertia of the controlled system, it incurs a delay between the actual temperature and desired temperature. The fuzzy controller was also testing on ability to react on disturbance from outside. In the time 9000 s the rate of flow of liquid B decreased as show Fig. 9. Figure 10 shows the increase of real temperature due to the disturbance. The controller

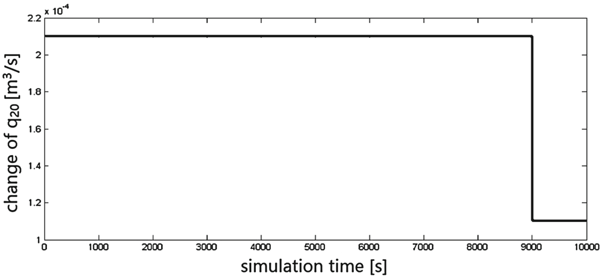

Fig. 9. Trend of real temperature (PV) and desired temperature (SP) with disturbance at 600 s

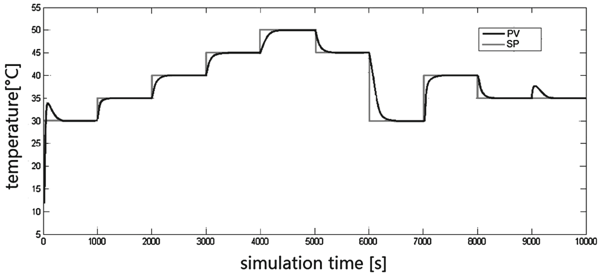

Fig. 10. Trend of actual temperature (PV) and desired temperature (SP)

responded correctly and in the time 9200 the real temperature and desired temperature were equal.

4 Conclusion

This study applied a fuzzy system for controlling heat transfer in indirect heat exchanger. The fuzzy system determines operating control parameters of heat exchanger based on the current states. The approach with the expert knowledge could obtain efficient and near-optimal solutions when compared to the simulation-optimization approach. The Fuzzy Control System was implemented in Programmable Logic Controller.

The virtual plant models and simulation models with other principles support companies in identifying and implementing Industry 4.0 scenarios. Based on the engineering experience, the fuzzy logic technologies have been developed to consider the problems of optimization and decision making in the presence of uncertainty. Many applications of fuzzy logic in industry have been successfully developed.

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