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MULTIVARIABLE FUZZY LOGIC CONTROL OF THE HEXAMETHYLENE TETRAMINE REACTOR

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ABSTRACT. The paper presents the simulation results of the Fuzzy Logic Control (FLC) of the hexamethylene tetramine reactor. Fuzzy Logic has become a valuable control strategy for chemical processes, due to its natural and intuitive way of representing information. Simulation results reveal its efficiency in terms of the main control performance indexes. The control difficulties generated by the multivariable approach and non-linear process behavior have been overcome by this control technique, with real possibility for industrial implementation.

INTRODUCTION

Fuzzy Logic control is obviously one of the most important control approaches developed during the last two decades. In the past few years, it has become a widely accepted control method in process industry plants, consecutive to the practical validation of the theoretical concepts. The possibility of creating software products that embed the simple *if...then* clauses used in natural language has been a major contributor to the success of fuzzy logic control. Indeed, fuzzy logic controllers can be designed to benefit of the knowledge accumulated by highly trained process operators, by directly transforming it into fuzzy inference rules. This often regularly creates more robust controllers, able to deal with process uncertainties and complex dynamic behavior (difficult to describe by first-principle models).

MODEL DESCRIPTION

The fuzzy logic approach has been tested for the control of the hexamethylene tetramine reactor (Ungureanu [1]). The stoechiometry of the reaction is described by:

$$4NH_3 + 6CH_2O \rightarrow N_4(CH_2)_6 + 6H_2O \quad (1)$$

A number of simplifying assumptions have been considered for modeling the reactor: the process is assumed to take place in a Continuous Stir Tank Reactor (CSTR), with no heat loss to the environment, irreversible third-order reaction mechanism and an Arrhenius type rate constant. The simplified mathematical model was experimentally validated and consists of a set of differential equations describing the main mass and energy balance:

$$\frac{dC_A}{dt} = \frac{q_A}{V} C_{A_i} - \frac{q_A + q_F}{V} C_A - r \qquad (2)$$

$$\frac{dC_F}{dt} = \frac{q_F}{V} C_{F_i} - \frac{q_A + q_F}{V} C_F - 1.5 \cdot r \qquad (3)$$

$$\frac{dT}{dt} = \frac{q_A}{V} T_{A_i} + \frac{q_F}{V} T_{F_i} - \frac{q_A + q_F}{V} T + \frac{(-\Delta H)}{\rho\ C_p} r - \frac{K\ A \Delta T_m}{V \rho C_p} \qquad (4)$$

where

$$r = k_0 C_A C_F^2 \exp\left(-\frac{E}{RT}\right) \qquad (5)$$

$$(-\Delta H) = -78.968 \cdot 10^6 + 0.50645 \cdot 10^6 \cdot T \qquad (6)$$

$$\Delta T_m = \frac{T_{r_0} - T_{r_i}}{\ln\left(\frac{T - T_{r_i}}{T - T_{r_0}}\right)} \qquad (7)$$

$$\frac{K\ A \Delta T_m}{V \rho C_p} = \frac{\rho_r C_r}{\rho C_p} \frac{q_r}{V} \left(T - T_{r_i}\right) \cdot \left[1 - \exp\left(-\frac{K A}{\rho_r C_r q_r}\right)\right] \qquad (8)$$

The main process variables taken into consideration are the outlet concentrations of ammonia and formaldehyde and the outlet temperature (as outputs), and the inlet flows of ammonia, formaldehyde and cooling agent (as inputs).

In despite of its fairly basic structure, the model is able to describe the dynamic features of the process that are used for control purposes.

RESULTS AND DISCUSSION

A fuzzy inference system is made of several rules using the same output variables. The inference procedure defines the way the conclusions are to be inferred using this set of rules. Output variables can be discrete ('crisp') or continuous, the inference system being called, respectively, a Sugeno or a Mamdani system.

Fuzzy reasoning works just like any other logical reasoning: a fuzzy conditional rule is made up of a *premise* and a *conclusion*

if premise ***then*** conclusion (9)

The premise may contain a number of predicates P_i, also called antecedents. The antecedents can be negated or combined by operators like AND, OR (computed with t-norms, or t-conorms). Based on the concepts introduced, a fuzzy conditional rule would be or the following form (M. Russo[2]):

if P_1 ***and*** P_2 ***or*** P_3 ***then*** P_4 (10)

where P_4 is referred to as the *consequent*.

Any process controller's mission is to receive a number of inputs and compute the appropriate outputs in order to eliminate a possible error. The fuzzy controller is no exception: it receives a measured value from the system (which is the universe of discourse), if fuzzyfies it, applies the conditional rules, computes an overall result of all the rules and then converts the result into a number which is an appropriate command for the system it controls. (Em. Sofron et. al.[3])

A multivariable controller has been used to control the three considered outputs. The parameters of the FL controller have been adjusted to account for the nonlinear features of the process and the interactions between the target variables.

First, the setpoint tracking capabilities of the FLC have been investigated using a step increase of the setpoint. The evolution of the three controlled outputs in case of a step increase of the setpoint (+0.4 kmol/m^3 at t=2000 s) of the ammonia outlet concentration is presented in Fig. 1.

Simulation results reveal the good performance of the FL controller. The controller is capable of leading the system to the new ammonia concentration setpoint value in a short time and with minimum overshoot. Also, no important deviation is induced on the evolution of the other controlled outputs of the system.

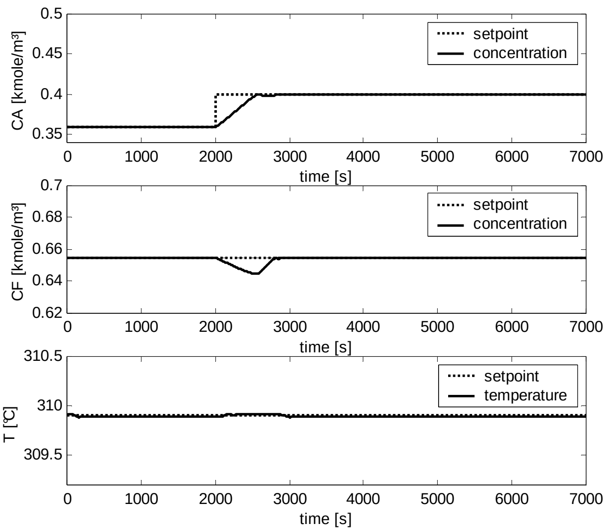

Fig. 1: Fuzzy Logic Control for the case of a step change in the setpoint of the ammonia concentration

The evolution of the controlled outputs in case of a step decrease in the setpoint (-5℃, at t=2000s) of the outlet temperat ure is presented in Fig. 2.

Again, a good setpoint tracking performance was obtained, accompanied by an efficient reduction of the interaction effect between the controlled outputs.

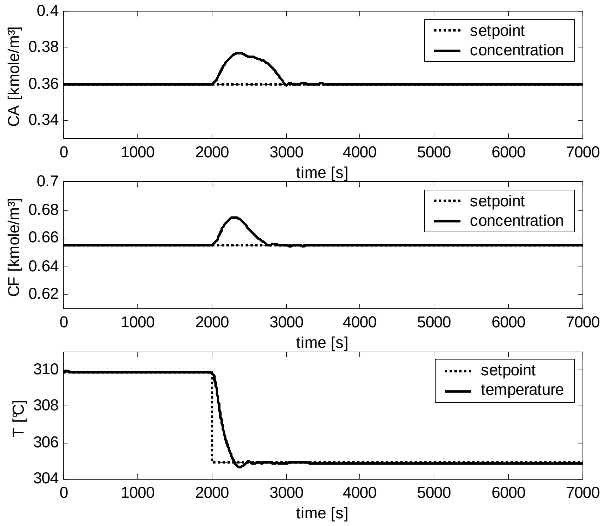

Fig. 2: Fuzzy Logic Control for the case of a step change in the setpoint of the outlet temperature

Second, the disturbance rejection ability of the controller has been tested. The results are presented in figures 3 and 4.

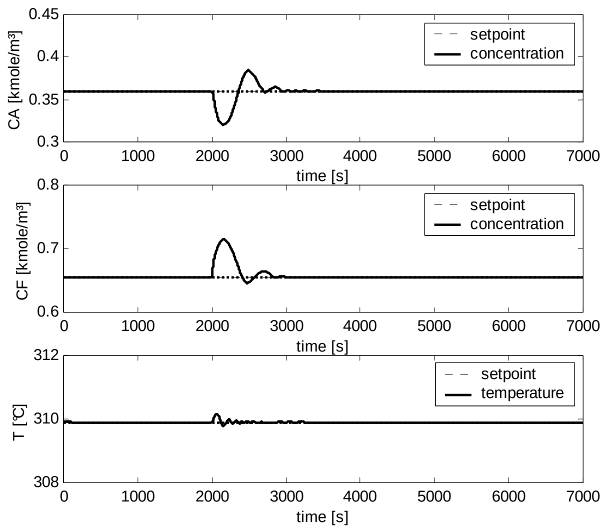

Fig. 3: Fuzzy Logic control for the case of a formaldehyde inlet concentration disturbance

Three typical disturbances have been considered: concentration of the inlet ammonia flow, concentration of the inlet formaldehyde flow and the inlet temperature of the cooling liquid. Simulation were carried out for the case of an increase (+0.6 kmol/m^3 at t=2000s) in formaldehyde concentration and for an increase (+6.8 ℃, at t=2000) in cooling liquid tem perature.

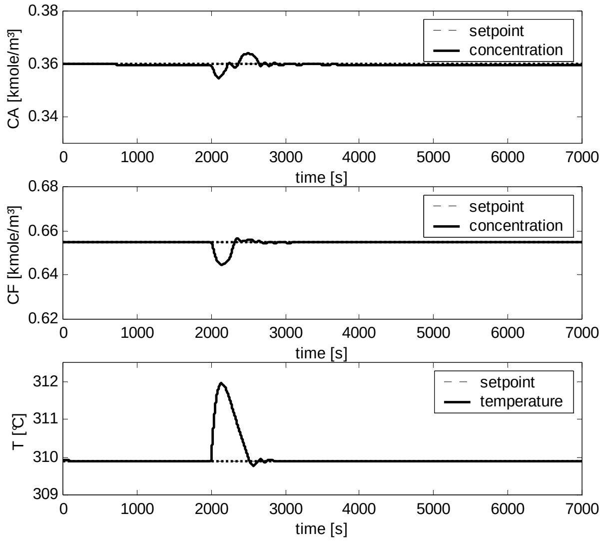

Fig. 4: Fuzzy Logic Control for the case of a cooling agent temperature disturbance

The controller performs very well in rejecting the tested disturbances. Low overshoot and minimum settling time are to be noticed. This good performance is due to the particular design of the fuzzy inference system: detailed fuzzification and defuzzification of the controlled systems inputs and outputs, each input and output using five membership functions (MF) and an asymmetrical membership function structure. This setup uses a total of fifteen fuzzy rules. MFs are of triangular shape. Their asymmetrical setup assists the controller in dealing with the difficulties induced by the non-linear system. A sample asymmetrical MF structure is depicted in Fig. 5.

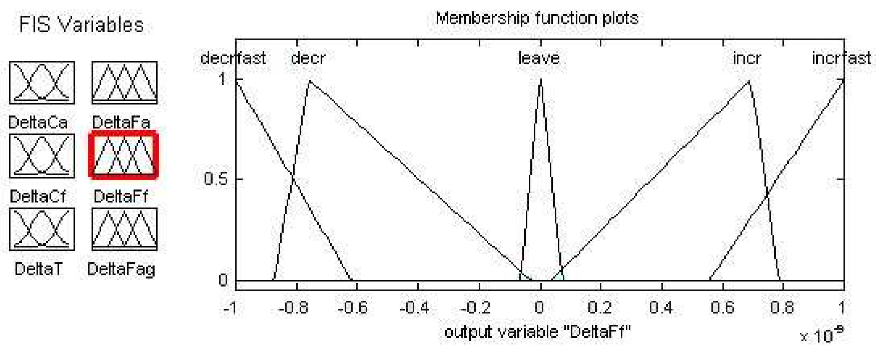

Fig. 5: Membership function structure for the defuzzification of formaldehyde flow rate

The model was coded as a Matlab S-function (Matlab [4]) and simulations were carried out using the Matlab extension, Simulink, in association with other dedicated Matlab toolboxes.

CONCLUSIONS

The present work investigates the possibility of implementing a fuzzy logic algorithm for controlling the hexamine CSTR. A multivariable (three-input and three-output) fuzzy-logic controller is developed and tested. The asymmetrical membership function definitions and fifteen rules are found to be capable of countering the system's nonlinear features, with minimal overshoot and short settling time. The controller exhibits good setpoint tracking performance and efficiency in rejecting disturbances. The controller is designed to minimize the interaction between the controlled variables.

All these features indicate that fuzzy logic control is a feasible approach to the control of process plants, for both large-scale and pilot-sized units.

NOMENCLATURE

C_P = mean heat capacity [J/kg K]
E = activation energy [J/kmol]
K = heat transfer coefficient [W/m^2 K]
k_0= frequency factor [(kmole/m^3)$^{-2}$ s^{-1}]
q = flow rate [m^3/s]
R= gas constant [J/kmol K]
r = reaction rate [kmol/m^3 s]
T= temperature [K]
V= reactor volume [m^3]
ΔH= reaction enthalpy [kJ/kmol]
ΔT_m= logarithmic mean temperature difference

Indices:
A= ammonia
F= formaldehyde
i= input
m= mean
r= cooling agent

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