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Control of a distillation column by type-2 and type-1 fuzzy logic PID controllers

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ABSTRACT

The aim of this paper is to develop a type-1 and a type-2 fuzzy logic PID controller (type-1 FLC and type-2 FLC, respectively) for the control of a binary distillation column, the mathematical model of which is characterized by both high nonlinearities and parameter uncertainties. Attention was focused on the tuning procedure proposed by the authors and representing a development of the original Jantzen [1] method for type-1 and type-2 fuzzy controllers, in particular including input type-2 Gaussian membership functions. A theoretical explanation of the differences in fuzzy controller performance was in fact provided in the light of simulation results. The performance of a type-1 FLC was then compared in simulation with the one of type-2 FLC. All the simulation results confirmed the robustness and the effective control action of each fuzzy controller, with evident advantages for the type-2 FLC.

1. Introduction

It is well known that the control of many industrial chemical processes characterized by high nonlinear dynamics and parameter uncertainties does not give satisfactory responses using conventional controllers. It is true that type-1 fuzzy logic controllers (type-1 FLCs) [2] have been reported to be successfully used for a number of complex and nonlinear processes, often coupled with an optimal control: Karr et al. [3] developed a fuzzy control of an exothermic chemical reaction using genetic algorithms; Çetinkaya et al. [4] used a fuzzy-relational models-dynamics matrix control for an optimal temperature control in a batch polymerization reactor; Shahraz and Bozorgmehry Boozarjomehry [5] proposed a fuzzy sliding mode control approach for nonlinear chemical processes; while Lima et al. [6,7] designed a fuzzy model-based predictive controller to control polymerization processes and proposed the application of predictive control using fuzzy logic for a polymerization system.

Despite their popularity, scientific research has recently shown that in many cases type-1 FLCs can have difficulties in minimizing the effect of uncertainties in the plant model, which are often responsible for the degradation of the same process control. Therefore, the choice of type-1 FLCs and then of type-1 fuzzy sets [8] may not always represent the optimal solution to a control problem, whereas a possible alternative is using type-2 fuzzy logic controllers (type-2 FLCs) that make use of type-2 fuzzy sets [34,47] characterized by a larger number of parameters and, as a consequence, of freedom degrees. The type-2 fuzzy logic control has been applied in many fields like anesthesia control [43], level control [9], marine diesel engine control [10] and more recently vehicle nonlinear active suspension systems [11], autonomous mobile robot control [46], cable-driven parallel mechanism [12], Kundur test system [13], biochemical reactor control [14–17], continuous stirred tank reactor [18] and inverted pendulum model [19].

Fuzzy logic has been applied to control of a distillation column, too. Luo et al. [20] developed a fuzzy-neural net-based inferential control for a high purity distillation column, while a neuro-fuzzy modeling and control of a batch process involving simultaneous reaction and distillation was developed by Wilson and Martinez [21]. More recently Fabro et al. [22] proposed a startup of a distillation column using intelligent control techniques (fuzzy sets optimized by genetic algorithms), Worapradya and Pratishthananda [23] developed a real-time control of a binary distillation column using HGA fuzzy supervisory PI controllers; Fernandez de Canete et al. [24] applied an adaptive neurofuzzy control using soft sensors to continuous distillation; the control of binary distillation column using PI controllers was proposed by Javadi and Hosseini [25]; while Barceló-Rico et al. [26] realized the modeling

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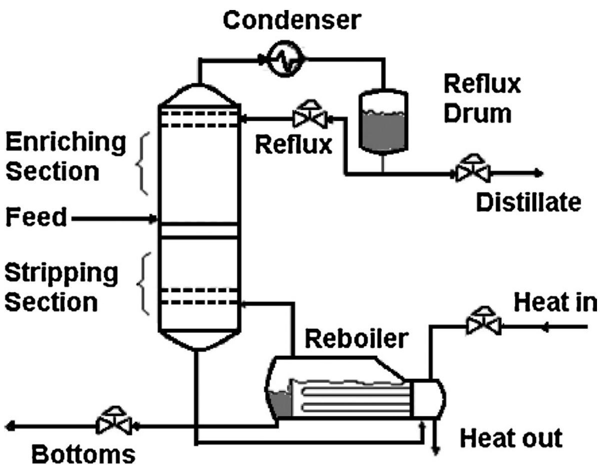

Fig. 1. Distillation column.

and the control of a continuous distillation tower through fuzzy technique. Other control strategies were applied to the distillation column as an inferential control system of distillation compositions using dynamic partial least squares regression by Kano et al. [27,28]; a globally linearized control system design of a constrained multivariable distillation column was instead developed by Jana et al. [29]; Bezzo et al. [30] used a model predictive control for middle-vessel continuous distillation columns; Kawathekar and Riggs [45] realized a nonlinear model predictive control of a reactive distillation column; a nonlinear adaptive control algorithm for a multicomponent batch distillation column was developed by Murlidhar and Jana [48]; and Sivakumar et al. [31] used a fuzzy model predictive control in multivariable control of distillation column.

The main aim of the distillation control method developed in this paper is to reach the set point value for the head concentration x_1 starting from a given initial condition and, above all, to have x_1 tracking the set point, despite the variation of the system parameters, in particular of the relative volatility α.

2. Materials and methods

2.1. Distillation column model

The system model, here considered, is a conventional two-component distillation column (Fig. 1) [32,33]. It is well known that distillation is based on the separation of two or more components of a liquid mixture by virtue of the differences in boiling points of the components. Fractional distillation is the most common form of separation technology used in petroleum refineries, petrochemical and chemical plants. Design and operation of a distillation column depends on the feed and desired products. The feed, i.e., the mixture to be separated, enters the central section of the column as a liquid, a liquid–vapor mixture or a vapor. The "stripping section" is the name given to the part of the column below the feed section. In this section the concentration of the more volatile component decreases. The "enriching section" is instead the name given to the part of the column above the feed section. In this section the concentration of the more volatile component increases. On the top of the column there is a condenser, the overhead vapor containing the most volatile components from the feed moves from the top of the column to the condenser and the condensate is collected in a tank from which the distillate and the reflux are taken. The reflux is fed back to the head of the column to provide liquid flow above the feed point (as it is necessary to keep the liquid flow rate constant) and it moves down the column in countercurrent flow with the vapor flowing up the column. The distillate (i.e., overhead product) contains liquid with the same composition specified in the design of the distillation column. On the bottom there is a reboiler. The residue is taken from the bottom as a liquid stream, then it is partly vaporized in the reboiler and re-introduced in the column where flows back up the column in countercurrent with the liquid moving down the column.

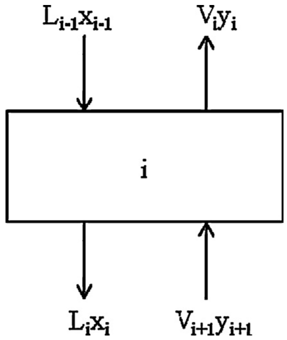

Fig. 2. Generic equilibrium stage.

The trays of a distillation column represent distillation stages, where some of the vapor moving up the column is condensed and some of the liquid moving down the column vaporizes. The trays are characterized by many holes or bubble caps to allow the vapor to pass through. Their utility is that to increase the contact time between the vapor and the liquid in the column. If there are two components in a liquid feed (as in this case study), a greater amount of the more volatile component will vaporize and a larger amount of the less volatile component will remain in the liquid condensate. In the simplest limiting case, the substance with the lower boiling point will condense in the top condenser and the species with higher boiling point will leave the bottom of the column as a condensed liquid. The application of the column distillation considered in the paper regards the separation of liquid streams containing two components (binary mixture). As in a mixture of benzene and toluene, the first is the light component (the component that boils at lower temperature) and the second one is the heavy component (the component that boils at a higher temperature).

The dynamical mass balance on the component in the generic stage (Fig. 2), excluding the feed stage, the condenser and the reboiler, is as follows:

$$\frac{dM_i x_i}{dt} = L_{i-1}x_{i-1} + V_{i+1}y_{i+1} - L_i x_i - V_i y_i \tag{1}$$

The steady state assumption holds for the overall mass balance; therefore, it is:

$$V_i = V_{i+1} \tag{2}$$

$$L_i = L_{i+1} \tag{3}$$

The overall mass balances for the feed tray (Fig. 3) are:

$$V_{nf} = V_{nf+1} + F(1-q) \tag{4}$$

$$L_{nf} = L_{nf+1} + Fq \tag{5}$$

where q is the rate (percentage) of liquid present in the feed and is expressed as:

$$q = \frac{L_{nf} - L_{nf-1}}{F} \tag{6}$$

whereas its complement to 1 $(1-q)$ represents the rate of vapor present in the feed.

The overall mass balance in the condenser is:

$$L_D + D = V_2 \tag{7}$$