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Dynamic vapor recompression in a reactive batch rectifier: Analysis and nonlinear control

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ABSTRACT

This work proposes a dynamic vapor recompressed batch reactive rectifier (VRBRR) for the butyl acetate system that operates with a dynamic compression ratio (CR). In this configuration, along with the CR, we manipulate either the overhead vapor inflow rate to the compressor or the external heat input to the reboiler for the purpose of coupling the thermal arrangement with the existing batch tower. To improve the product purity and the amount of distillate collection of the dynamic VRBRR, we further formulate a nonlinear extended generic model controller (EGMC) that requires state information for its simulation. For this, we develop a closed-loop high gain observer (HGO) for estimating a limited number of states, exclusively required for the EGMC. This results in a significant structural mismatch that is taken care of by the hybrid EGMC-HGO system. For the representative butyl acetate system, it is investigated that the proposed nonlinear controller outperforms a traditional PI controller in regulating the dynamic VRBRR.

1. Introduction

The dependency on fossil fuels of the modern human civilization has been increasing enormously with the gradual progress of industrial revolution. Apart from the severe concern of its consistent availability owing to its increasing demand [1,2], indiscriminate burning of fossil fuels releases CO_2, which is one of the principal greenhouse gases (GHG) responsible for global warming and its adverse effects [3]. As a preventive measure, we show our interest to improve the thermal efficiency of industrial processes. In this regard, process intensification route is a viable alternative in order to obtain ultimate cheaper and sustainable technologies, by utilizing every possible source of waste heat.

As an essential unit operation [4], distillation/rectification always attracts researchers as a major area of energy intensification. The existing schemes of energy integration can be categorized into two classes namely, internal and external heat integration. Popular examples of the internal and external heat integrated schemes are the heat integrated distillation column (HIDiC) [5] and vapor recompression column (VRC) [6], respectively.

The first research work was published in the area of energy intensification in 1960s [7]. It showed its superiority to enhance the energy performance of the system, and thus emerged as a popular thermal integration approach. On the other hand, Takamatsu et al. [8] first proposed a thermally coupled batch distillation configuration where we observe the incorporation of a jacketed reboiler surrounding the rectifying tower. Jana and Maiti [9] subsequently evaluated the advantage of this novel scheme over its conventional counterpart, in terms of energy efficiency and cost.

Jana and his co-workers [10,11] proposed "variable speed" VRC scheme, and applied on energy efficient unsteady state batch distillation operation. This variable speed mechanism is further illustrated on a ternary batch distillation column having side withdrawals [12] and also on a batch distillation column containing a feed drum in between its rectifying and stripping section [13].

Apart from the feasibility analysis, Babu and Jana [14] in their recent communication used a closed-loop gain scheduled PI (GSPI) control structure on the variable speed vapor recompressed batch distillation column to achieve relatively high purity top product at a constant composition. Being nonstationary and nonideal in nature, heat integration in batch distillation and thereby its control is really a challenging task and to the best of our knowledge possibly no nonlinear model-based control scheme is available so far in the open literature showing its applicability on vapor recompressed column. It is with this intention the present work has been undertaken.

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Here, we designed a nonlinear model-based extended generic model controller (EGMC) [15,16] based on differential geometry theory. This EGMC controller serves as a bridge between classical GMC [17] and generalized GMC [18]. The nonlinear EGMC controller so developed requires information about specific internal states of the process that are inevitably required for its simulation, and hence, we develop the reduced order nonlinear high gain observer (HGO) unlike EKF [19], ELO [20], etc. By continuous updating state information required for controller simulation, this nonlinear high gain observer (HGO) is capable of reducing the effect of structural discrepancy that generally arises due to the use of reduced order process model while developing a model-based controller.

As per our present contribution is concerned, we focus our attention primarily on the implementation of the vapor recompressed batch reactive rectifier (VRBRR) scheme involved in the production and separation of butyl acetate (BuAc) as distillate. This work is an extension of the investigation conducted by Jana and Maiti [9] on the present BuAc system based on operating compression ratio (CR) at static mode. Aiming to achieve constant product purity and more amount of distillate collection, the closed-loop performance of the energy efficient dynamic VRBRR column is evaluated. For this purpose, the model-based EGMC controller is developed and subsequently coupled with a nonlinear model-based high gain observer (HGO) that serves as a state estimator solely required for the controller simulation. The closed-loop dynamic VRBRR under HGO-based EGMC control scheme proves its superiority over a traditional PI controller regarding energetic and economic aspect, product purity, as well as amount of distillate collection.

2. Process modelling

The mathematical model of the vapor recompressed batch reactive rectifier (VRBRR) can be classified into two segments, namely modelling of the tray tower and modelling of the compressor. In general, we consider the following assumptions for model development: perfect mixing and equilibrium on all stages, vapor hold-up is negligible compared to liquid hold-up which varies in each tray, the energy dynamics of the column are fast, chemical reactions are confined to reactive zone and take place only in the liquid phase, constant Murphree plate efficiency based on the vapor-phase (=75%) is considered, the compressor installed between the overhead vapor and bottom reboiler is isentropic, and difference in temperature between the compressed overhead vapor and reboiler is at least 20 °C.

Modelling of the tray tower is elaborately discussed by Jana and Maiti [9], so in this paper we only concentrate on the modelling of the compressor.

2.1. Modelling of the compressor

The compressor duty of the VRBRR can be represented by the following mathematical equation [21]:

$$Q_{Comp} = \frac{V_{n_T C}\mu R T_{n_T}}{\mu - 1}\left[(\mathrm{CR})^{\frac{\mu-1}{\mu}} - 1\right] \tag{1}$$

In the above equation, Q_{Comp} depicts the compressor duty, $V_{n_T C}$ the flow rate of the compressed overhead vapor, T_{n_T} the corresponding temperature and R the universal gas constant. The CR represents the compression ratio and it can be represented by:

$$\mathrm{CR} = \frac{P_{n_T C}}{P_{n_T}} = \left(\frac{T_{n_T C}}{T_{n_T}}\right)^{\mu/(\mu-1)} \tag{2}$$

The polytropic coefficient μ is a function of temperature and it can be calculated from the following equation:

$$\frac{1}{\mu - 1} = \sum_{i=1}^{N_C} \frac{y_i}{\mu_i - 1} \tag{3}$$

Here, P_{n_T} and $P_{n_T C}$ are the pressure of overhead vapor and compressed vapor that correspond to T_{n_T} and $T_{n_T C}$, respectively.

3. Development of VRBRR

The prime objective in developing the vapor recompressed column is the optimal utilization of available internal source of energy with the aim of reducing the capital as well as operating costs. Fig. 1 depicts the requisite transformation from conventional to vapor recompressed column.

3.1. Categorizing VRBRR based on mode of operating CR

The gradual development of the VRBRR scheme based on static and dynamic CR is discussed in the following subsection and accordingly, names of the corresponding VRBRR are given as static VRBRR and dynamic VRBRR.

3.1.1. Static VRBRR

As the name suggests, static VRBRR refers to the operation of the rectifier at static (fixed speed) CR mode. The difference in temperature (ΔT_C) between the compressed vapor ($T_{n_T C}$) and the reboiler liquid (T_B) serves as the thermal driving force, and this is essential for latent heat transfer from the former to the latter stream. It is true that because of the transient nature of the batch processing, both the overhead vapor temperature (T_{n_T}) as well as the reboiler liquid temperature (T_B) vary with time. As stated, apart from constant reboiler heat duty (Q_R) to operate the VRBRR at static CR mode, the necessary condition which must be satisfied is $\Delta T_C \geq 20$ °C [9].

3.1.2. Dynamic VRBRR

Dynamic VRBRR comes into the picture when we wish to operate the compressor at a controlled CR. It is done with the aim to avoid unnecessary overheating of the overhead vapor prior to its thermal interaction with the reboiler liquid. To achieve this, the important criterion, which needs to be fulfilled apart from constant reboiler energy demand (Q_R) is $\Delta T_C = 20$ °C.

Accordingly, the following equation can be used which is the extended form of Eq. (2)

$$\mathrm{CR} = \frac{P_{n_T C}}{P_{n_T}} = \left(\frac{T_{n_T C}}{T_{n_T}}\right)^{\mu/(\mu-1)} = \left(\frac{\Delta T_C + T_B}{T_{n_T}}\right)^{\mu/(\mu-1)} \tag{4}$$

The necessary adaptation of the CR value at each and every time step is made with the help of the above equation. In the dynamic VRBRR scheme, apart from adjusting the CR, either the vapor inlet to the compressor or the external source responsible for supplying heat to the bottom reboiler needs to manipulate simultaneously. The mechanism is described below.

3.2. Mechanism for variable manipulation

As per the availability of heat with the compressed vapor (Q_{CV}) compared to the reboiler energy demand (Q_R), we can categorically divide it into three schemes [Scheme 1 (when $Q_{CV} < Q_R$), Scheme 2 (when $Q_{CV} > Q_R$) and Scheme 3 (when $Q_{CV} = Q_R$)]. This strategy of variable adjustment for the VRBRR is applicable equally to its static as well as the dynamic mode of operation to ensure the optimal use