Control of Ethylene Glycol Reactive Distillation Column

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Kumar and Daoutidis (1999) studied the control of an ethylene glycol reactive distillation column and concluded that an advanced nonlinear inverse-based controller is needed. The purpose of this article is to demonstrate that a simple single-temperature proportional integral (PI) structure provides effective control.

Only a handful of articles have explored the control of reactive distillation columns. A review of recent literature is given by Al-Arfaj and Luyben (2000). We have studied a number of reactive distillation columns (Al-Arfaj and Luyben, 2002a,b,c) and have found that effective control is provided by simple PI control schemes if appropriate management of feedstreams and product purities is provided.

The chemistry in the ethylene glycol process is the irreversible reaction of ethylene oxide with water to form ethylene glycol. There is a second consecutive reaction in which ethylene oxide reacts with ethylene glycol to form di-ethylene glycol. We use the kinetics given by Kumar and Daoutidis (1999). The steady-state design and the dynamic simulations use the commercial simulators Aspen Plus 10.2 and Aspen Dynamics 10.2. This study demonstrates the value of dynamic simulation in the analysis of alternative control schemes for complex unit operations.

Column Design

The only optimized design available in the literature for the ethylene glycol reactive distillation process is the one proposed by Ciric and Gu (1994). However, their optimum design uses impractically large tray holdups (1.5 m^3), which would mean excessive liquid height and pressure drop for the column diameter and production rate used in their article. They also used ideal vapor-liquid equilibrium and an operating pressure of 1 atmosphere.

Based on the work of Okasinski and Doherty (1998), we increased the pressure to 15 atmospheres and used the Wilson VLE relationships. The higher temperatures yielded more practical tray holdup (0.1 m^3). The modified design is shown in Figure 1. Figure 2 shows the composition and temperature profiles. Note the very low ethylene oxide concentrations throughout the column.

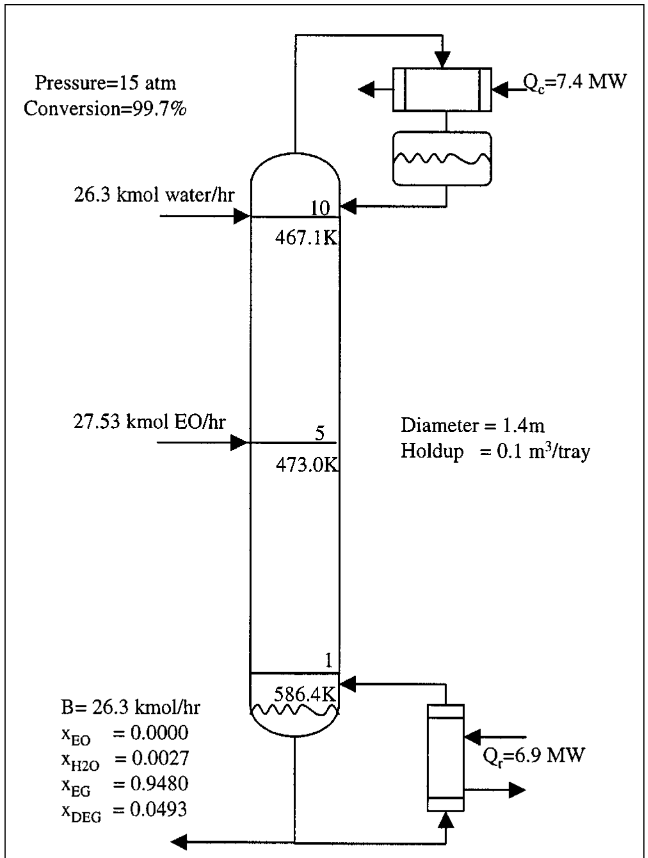

Figure 1. Ethylene glycol reactive distillation column.

Control Structure

The control objective is to maintain the ethylene glycol purity within the desired range. However, controlling product quality directly would require the use of an expensive and unreliable online composition analyzer. Simple temperature measurement to infer composition is preferable. In the ethylene glycol reactive column, there is a large temperature

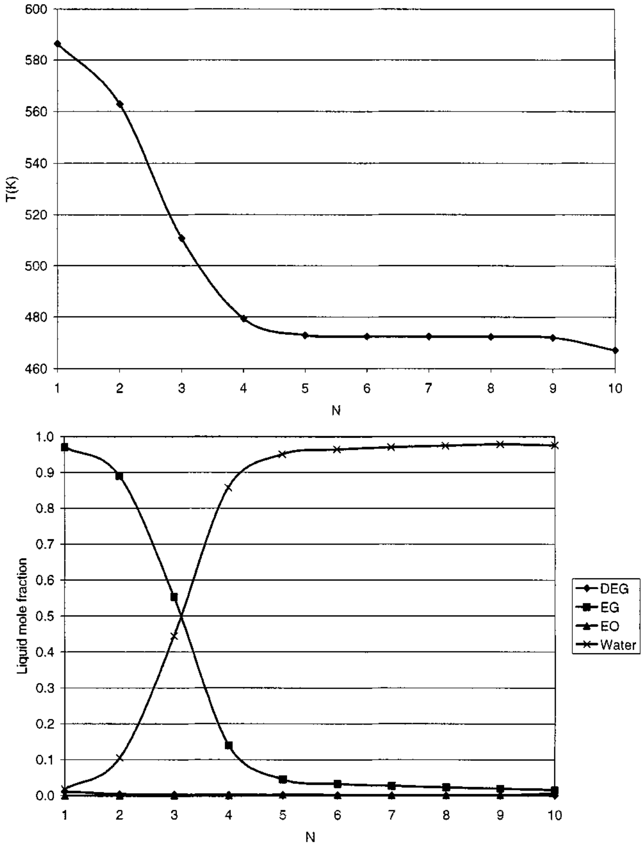

Figure 2. Temperature and composition profiles.

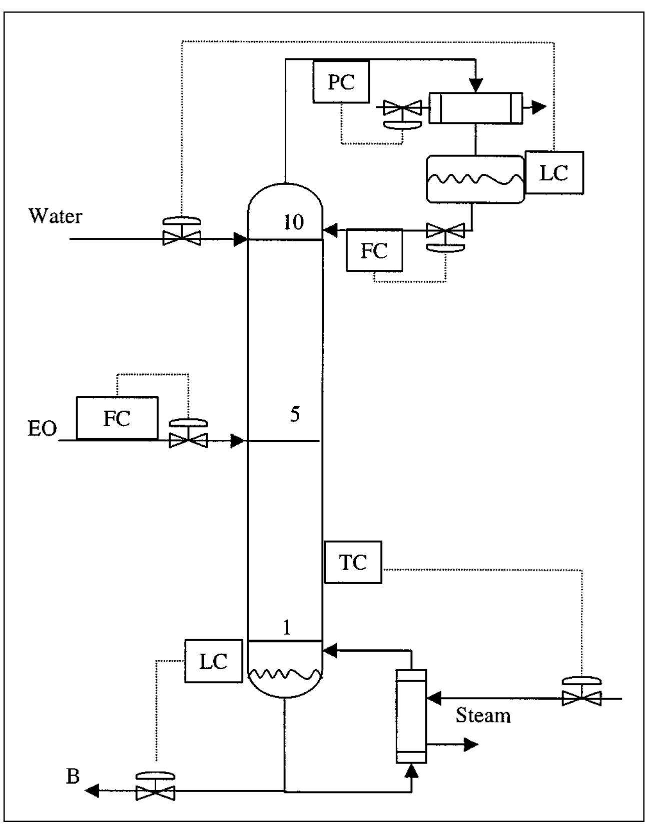

Figure 3. Control structure.

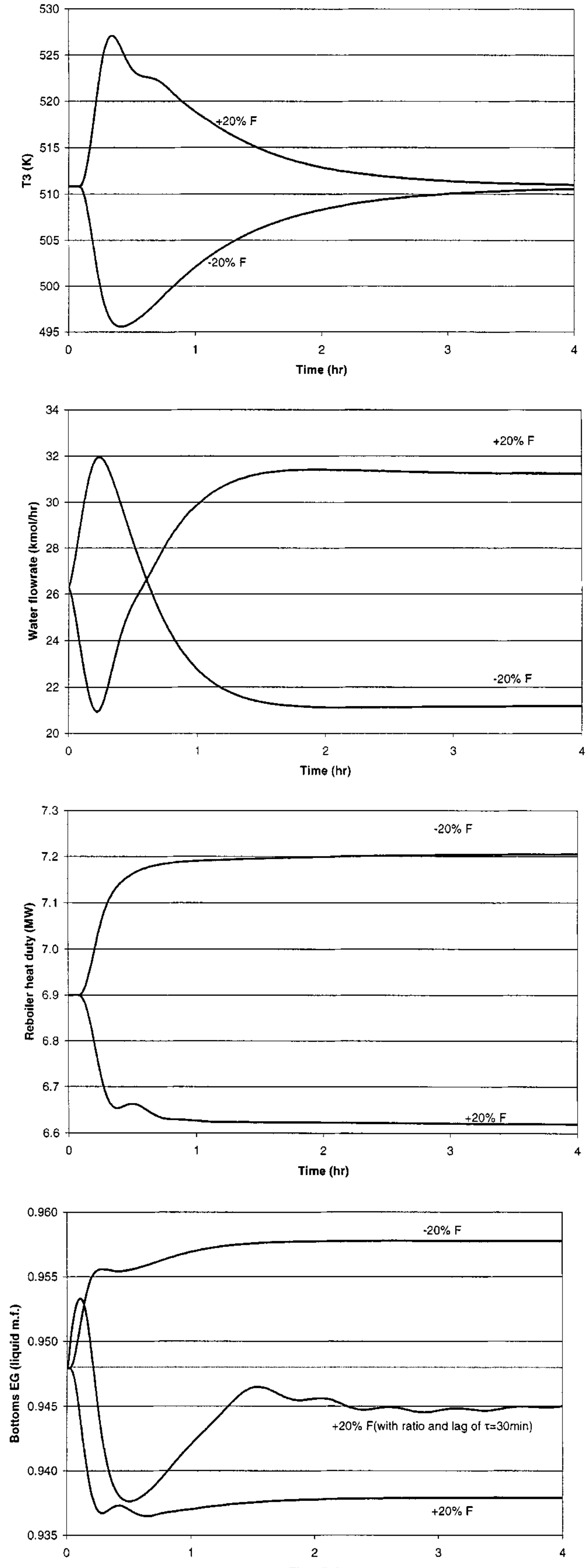

Figure 4. System response to feed disturbances.

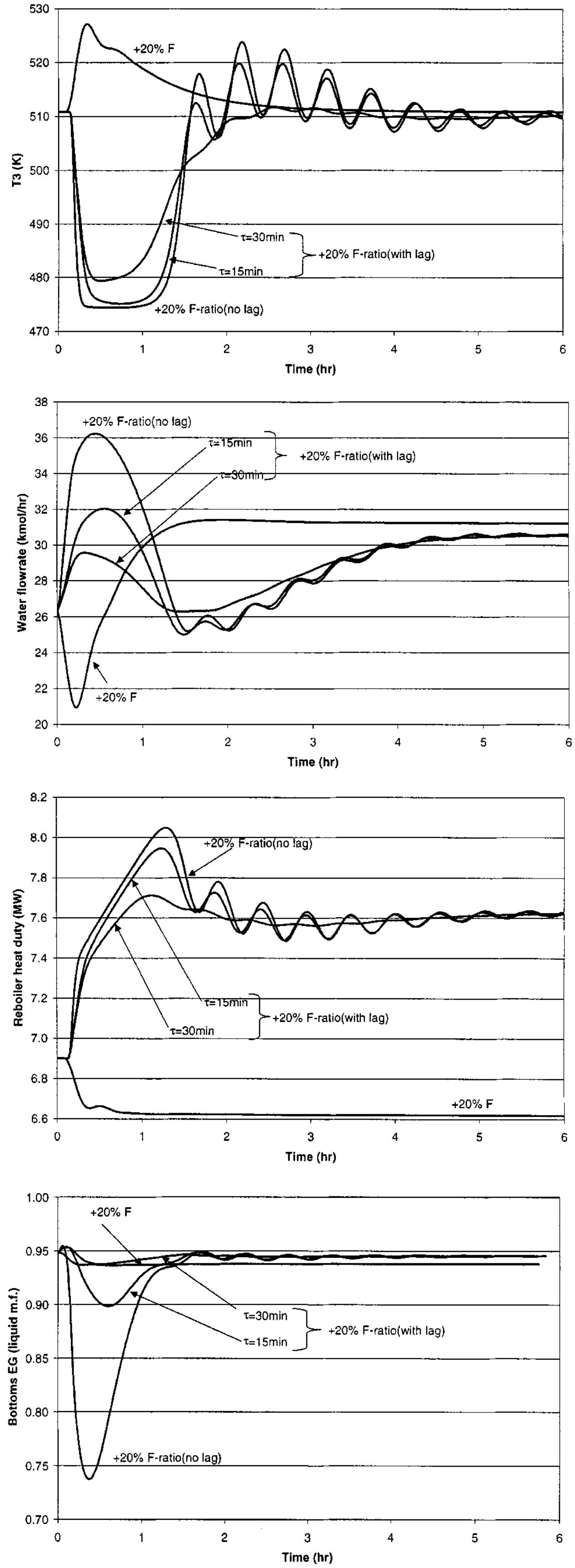

Figure 5. System response to feed disturbances with ratio control and lags.

change in the stripping section as the water is separated from the ethylene glycol. Therefore, we control the temperature on Tray 3 (numbering from the bottom) by manipulating reboiler heat input.

The ethylene glycol reactive distillation column is run essentially "neat" (that is, there is a little excess of ethylene oxide to compensate for the second reaction). An effective control structure must be able to perfectly balance the two fresh feedstreams. Ratioing the two feeds cannot work because of flow measurement inaccuracy. Some type of information feedback is required about the inventories of reactant components in the system.

In this process, the concentrations of ethylene oxide throughout the column are very small, and their conversion is essentially 100%. Therefore, we can flow control the fresh feed of ethylene oxide. This is the production rate handle.

The top of the column and the reflux drum are filled with essentially pure water. There is no distillate product. All of the overhead vapor is condensed and refluxed back to the column. The reflux-drum level provides a good indication of the inventory of water in the system. If this level is increasing, we know too much water is being fed into the system. The temperature controller prevents water from leaving in the bottoms. Essentially, all the water must react. Therefore, we control reflux-drum level by manipulating the makeup fresh feed of water.

The proposed simple PI control scheme is shown in Figure 3. The column pressure is controlled by manipulating condenser heat duty, and the column base level is controlled by manipulating bottoms product flow. The temperature control loop has a first-order lag with a time constant of 0.5 min and a deadtime of 4 min, which give very conservative estimates of performance. The temperature loop is tuned using the relay-feedback test (Yu, 1999) and Tyreus-Luyben settings.

Results

The responses of the system are shown in Figure 4 for $\pm$ 20% step changes in the flow rate of fresh ethylene oxide. The control structure provides effective basic regulatory control of the process. The water feed changes to balance the ethylene oxide feed. The system settles down after 3 h. The ethylene glycol purity is not maintained exactly at the desired value because a tray temperature is controlled, not product composition. However, even for this large disturbance, the error only is about 1%.

If less error is desired, an alternative control structure can be used. Ratioing the reflux flow to the ethylene oxide feed flow improves bottoms purity, as shown in Figure 5 (and the bottom right plot in Figure 4). The error is reduced to 0.5%.

It is important to use a dynamic element in the ratio circuit. If the reflux flow is changed instantaneously with the ethylene oxide feed, there is a very large drop in column control-tray temperature and in bottoms purity. Figure 5 shows that the use of a 30-min first-order lag in the ratio circuit gives good control, both dynamically and at steady state.

The control structure has many advantages over the complex control structure proposed by Kumar and Daoutidis. First, only simple conventional PI loops are used. Secondly, no composition analyzer is required. The structure can handle large disturbances.

Conclusion

This study demonstrates that ethylene glycol reactive distillation columns can be controlled effectively by a simple PI control scheme. The structure achieves the stoichiometric balancing of the reactants and maintains the product purity within reasonable bounds. This structure should be generally applicable to other systems that are similar to the ethylene glycol system in stoichiometry, kinetics, VLE, and design.

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