Process Intensification Modules in a Chemical Engineering Mass Transfer Course

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Abstract – Due to global economic competition, it is essential for companies to find more efficient methods for designing chemical production processes. One approach that industry is using is process intensification, where two or more traditional unit operations are frequently merged into a single unit operation. This often yields capital cost savings because fewer equipment units are needed, and also yields significant energy savings and savings in other operating costs. Process intensification often requires integrating concepts from multiple traditional chemical engineering courses. To help students integrate concepts from multiple courses and to prepare them for industrial careers, modules in process intensification are being incorporated into a mass transfer course. Two modules are presented: 1) a module on reactive distillation that combines a reactor with a distillation column, and 2) a module on dividing wall columns that integrates two distillation columns. Both of these modules are presented.

Keywords: mass transfer, process intensification.

INTRODUCTION

Traditionally in chemical engineering, courses have been taught by compartmentalizing unit operations into separate courses, with little integration of concepts between courses. That is, the details of heat exchangers, distillation columns, and chemical reactors are usually taught in three separate courses. In designing manufacturing plants, it is common to have a reaction section and a separation section of the process flow diagram. In these sections, the processing operations needed are identified and a unit operation is assigned to each processing operation. However, due to global economic competition, it is essential for companies to find more efficient methods for designing chemical production processes.

One approach that industry uses is process intensification. Process intensification frequently merges two traditional unit operations into a single unit operation, which often requires integrating concepts from multiple traditional chemical engineering courses. This often yields capital cost savings because fewer equipment units are needed, and also yields significant energy savings and savings in other operating costs [1, 2]. It has been observed that European universities and companies have placed more emphasis on process intensification and that efforts in the U.S. have lagged behind [2]. One barrier in the U.S. to implementing process intensification techniques is lack of education in this area [2] and the focus on only sequential unit operations [1].

To help students integrate concepts from multiple courses and to prepare them for industrial careers, modules in process intensification are being incorporated into selected core courses at Mississippi State University. Two modules are presented: 1) a module on reactive distillation, and 2) a module on dividing wall columns. The module on reactive distillation combines a reactor with a distillation column and therefore integrates reaction kinetics with mass transfer concepts. The second module on dividing wall columns integrates two distillation columns and concepts of mass and heat transfer. Both of these modules are presented.

The mass transfer course is taken by students during the spring semester of their junior year. The class size is typically 50 to 60 students. Although the students have not taken reactor design, they have taken chemistry courses that discussed reaction stoichiometry, reversible reactions, and multiple reactions. Many of the students have either completed or are concurrently enrolled in the heat transfer course. These modules are presented near the end of the

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semester after the basics of distillation column design are covered. Each module is typically presented in one 50 minute class period.

REACTIVE DISTILLATION

This module was developed for the Spring 2010 semester and was presented in both the Spring 2010 and Spring 2011 semesters. Before discussing reactive distillation, process intensification was presented so that students could understand why it was important.

The students were told that it has been stated that “any chemical engineering development that leads to a substantially smaller, cleaner, and more energy efficient technology is process intensification” [1]. That is, it can include any of the following items of any combination of these items.

- Reduction in plant or process size by combining units
- Reduction in raw material needs and less waste
- Reduction in capital and energy costs

Emphasis is placed on its significance for companies due to reduced costs and increased competitiveness, and its potential global and societal impact due to reduced waste and therefore environmental pollution. In discussing this with the students the potential of process intensification to make plants safer is also discussed.

The conventional approach of having reactions and separations occur in different units was presented before discussing the single unit approach. The production of methyl acetate was used as a case study [3, 4]. The basic reaction was presented as shown below.

$$\text{methanol} + \text{acetic acid} \leftrightarrows \text{methyl acetate} + \text{water} \quad (1)$$

The limitations on conversion due to the reversible reaction, and the challenges in separations due to two minimum boiling point azeotropes were also presented. As a base case, the conventional process has 30% conversion and uses 8 distillation columns. Therefore, it is a good candidate for process intensification.

One of the main challenges is finding a way to force the reaction to proceed to the right. It is explained that if products are removed, then the reaction does proceed forward. This leads to the concept of combining the reactor with a distillation column by having a reaction section in the distillation column. The benefits of this process are presented such as higher conversion. It is stated that this has been implemented by Eastman Chemical and that manufacturing cost was reduced by an order of magnitude. The students are able to understand that this would allow the company to make more profit from the production of methyl acetate.

As an in class activity, students were asked to answer the following questions.

1. How does a reactive distillation column differ from a non-reactive column?
2. What are some design differences?

The answers included the addition of a reaction section for the first question. Some of the differences are: accounting for the heat generated by the reaction, accounting for the reaction’s effect on the mass balances, and the effect of no recycle on the column size.

After reviewing the base case, a few other reactive distillation systems are mentioned. Also, it is stated that the process simulator ChemCAD has a reactive distillation example for the production of ethyl acetate in the examples that come with the software. Since the students in the class are required to use ChemCAD, they have access to the example problem.

Concluding Remarks

The reactive distillation module introduces students to basic concepts in process intensification. Specifically, it integrates concepts from reaction kinetics with distillation. Although the students have not taken the reaction kinetics course at this time, they have enough knowledge to grasp the concept of driving a reversible reaction to the right by removing products. Although they haven’t taken the design courses yet, they can still understand that reducing the number of distillation columns will reduce capital costs and energy usage. Therefore, this course qualitatively integrated concepts from other courses to solve a problem. In this module, the process intensification aspects of capital cost savings and energy savings were emphasized.

DIVIDING WALL COLUMNS

This module was added in the Spring 2011 semester. It was taught after the reactive distillation module was presented. Therefore, the students had already been introduced to process intensification. This module first introduced the Petlyuk column arrangement and then progressed to dividing wall columns.

The approach was to present two direct sequences of two simple distillation columns to separate a ternary mixture, then to present alternative configurations that had more thermal coupling [5]. Finally, the Petlyuk configuration was shown that has 2 columns, but only one reboiler and one condenser as shown in Figure 1. Other information was provided on thermal inefficiencies due to remixing in the direct sequences [6]. Comparisons between the direct sequence and the Petlyuk configuration included advantages of the Petlyuk configuration such as it having the lowest heat demand, disadvantages such as the limited range of feed compositions for where it is most efficient, and ideal conditions for Petlyuk use [6-8].

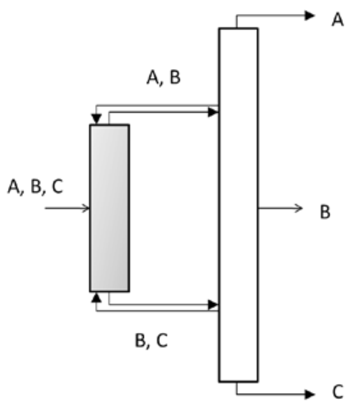

Figure 1. Petlyuk column configuration. Adapted from [5].

Then the dividing wall column (DWC) was presented in class where essentially two columns are combined into a single column with a dividing wall [6,8] as shown in Figure 2, where the dividing wall is represented by the thick vertical line in the center of the column. This builds on the concept of the Petlyuk column configurations and demonstrates that further integration of units is possible. It was explained that the single column reduces capital costs by only having one column, one condenser, and one reboiler. Instruction included discussing advantages such as the savings in capital and energy costs, and disadvantages such as complexity in controlling the column [6]. Other limitations were given including why a DWC cannot replace two columns operating at significantly different pressures. A brief review of the usage of DWCs in industry was presented and it was emphasized that this is a continuing area of research. For example, a paper was published in 2011 on potential energy savings in DWCs [9]. It was emphasized that there are alternatives DSC configurations based on where the dividing wall is located.

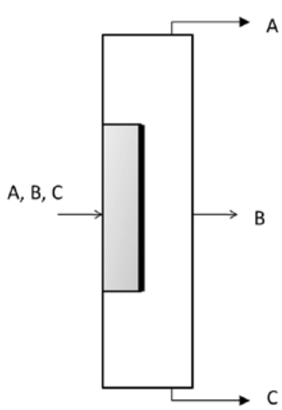

Figure 2. Dividing wall column schematic.

Concluding Remarks

The Petlyuk and dividing wall column module provides examples of process intensification. This is particularly true for DWCs where the process is reduced from two columns to one column. This course uses concepts from both the heat transfer course and the mass transfer operations course.

ASSESSMENT

Formal assessment on this project is being performed by a faculty member in the Department of Counseling and Educational Psychology as an independent assessor. Typically one survey is performed at the beginning of a class and the other pre/post survey is performed at the end of class when a module is presented. There is one survey for the reactive distillation module and one survey for the DWC module. The plan is to compare the course assessment results for each time it is offered.

For example, the pre/post survey used for the dividing wall columns module has the following questions.

1. In a Petlyuk arrangement of two distillation columns:
   a. each column has a reboiler and a condenser
   b. one column has a reboiler and a condenser, and the other column has a reboiler but no condenser
   c. one column has a reboiler and a condenser, and the other column has a condenser but no reboiler
   d. one column has a reboiler and a condenser, but the other column does not have a reboiler or a condenser
2. A dividing wall column is equivalent to a sequence of simple distillation columns with:
   a. two column
   b. three columns
   c. four columns
3. The main benefits from both Petlyuk and dividing wall columns come from:
   a. pressure differences
   b. simplified control
   c. thermal coupling
4. Advantages of dividing wall columns include which of the following (can circle more than one answer):
   a. lower operating costs
   b. lower capital equipment costs
   c. improved process performance

These questions are designed to determine if the students comprehended the fundamental concepts of Petlyuk columns and dividing wall columns. Specifically, the questions determine if the students knew the configuration of the columns and the benefits of using the columns.

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