DESIGN AND CONTROL FOR ENERGY INTEGRATION IN A BIO-PROCESS

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Abstract: This paper presents an industrial viewpoint on designing for energy integration in processes with substantial water removal (e.g. bio-processes) to ensure dynamic controllability. The use of evaporation and distillation for water removal and product purification in a bio-process is energy intensive, since the concentration of desired product leaving the fermenter is often quite low. The nature of a fermentation process causes inherent variation in the feed composition to downstream units. Potential opportunities for energy integration can be exploited, but must be done in a way that ensures the process is controllable. An example is presented of a multi-effect evaporator system combined with two distillation columns, describing how the design of energy integration between them requires some mechanism or manipulator to prevent disturbances from propagating around the material and energy loops.

Keywords: Distillation columns, integrated plant control .

1. INTRODUCTION

Many researchers and practitioners have recognized that the design of a chemical process (unit operations, process conditions and parameters, equipment layout, available measured and manipulated variables, etc.) plays a dominating role in determining how controllable the process is. Furthermore, it is economically advantageous to consider operability at the design stage rather than wait until after the process is built. Van Schijndel and Pistikopoulos (1999) provide a comprehensive summary of work on the integration of design, control, and operation.

The viewpoint in this paper (as in Downs and Doss, 1991) argues that controllability and control strategy design should not be simply an afterthought of the process design. Processes designed with a focus on inherently eliminating variability can often be controlled by relatively simple, straightforward, decentralized control strategies (rather than a focus on the development of complicated control algorithms). This paper uses an example of separations in a bio-based process to show how controllability can be designed into the flowsheet.

One area of new technology development within the chemical industry focuses on the use of renewable feedstocks (as opposed to those that use raw materials from petroleum) in biologically-based processes that produce chemicals and other materials. Such new processes will take some carbohydrate source (e.g. corn syrup) and convert it with microorganisms via fermentation into a desired product (Vanhoek and Reeder, 2003). The Cargill Dow process to make lactic acid (for use in production of polylactide polymer) is one example. The DuPont process to make 1,3-propanediol (for use in production of polytrimethylene terephthalate or 3GT polymer) is another.

One consequence of using microorganisms in a bio-process is that the desired product may leave the fermenter in a large amount of water. For example, product titer of 50 g/L translates into roughly 95 wt% water, depending on steps taken after fermentation. Many different separation technologies are practiced on the fermentation broth to produce the desired product with the required product quality and consistency. These include filtration (rotary drum, micro, nano, ultra, etc.), ion exchange beds, carbon beds, chromatography, evaporation, extraction, crystallization, distillation, and others. Two references, among many others, include Belter *et al.* (1988) and Subramanian (1998). The focus of this paper is on evaporation and distillation for water removal and product purification and how to design with energy integration to ensure the integrated process is controllable.

2. EVAPORATION

The technology of evaporation has existed for millennia (chapter 11 in Perry and Green, 1999, provides some general background). It is widely used in the food, beverage, sugar, dairy, mining, mineral, pulp, paper, pharmaceutical, health care, chemical, polymer, salt, seawater, and many other industries. The purpose of this paper is not to present specific details on evaporator design and operation. Much of that is available from vendors or the literature (e.g. Nisenfeld, 1985). There are many different types of evaporators including natural circulation, rising and falling film tubular, forced circulation, wiped film, plate, etc. The choice depends upon the heat sensitivity of the process materials, the viscosity or corrosivity, the scale and capacity, and the relative costs of steam and electricity.

Since evaporation is energy intensive, many techniques have been developed to conserve energy. One is the use of a multi-effect system, where the vapor produced in one effect becomes the heat source in the second effect at lower pressure (Figure 1). Another is the use of mechanical vapor recompression, where a fan or compressor increases the pressure of the evaporated vapor product which becomes the heat source. One important factor in evaporation is the boiling point rise, which is the difference between the boiling point of the solution and the boiling point of water at the same pressure. This governs many of the process conditions and evaporator types.

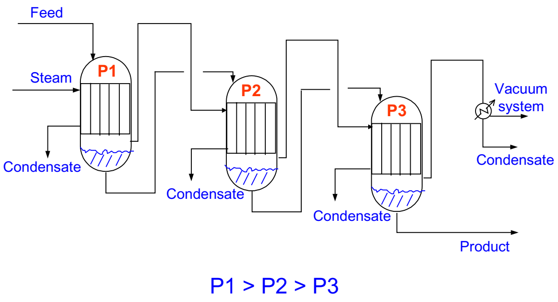

Fig. 1. Multi-effect evaporation system

3. BIO-PROCESS EXAMPLE

A generic bio-process shown in Figure 2 contains downstream steps for the removal of water and other impurities. The desired product from the fermenter may be more or less volatile than water. Some alcohols, for example, may be more volatile then water. The process design would be different from what is presented here, but the same controllability issues and principles apply. In this particular example, water is assumed to be the lightest component. Three other components A, B, and C are present (in order of decreasing volatility). Component B is the desired product. The feed stream of 150 kmol/h contains 0.97 mol frac water, 0.007 mol frac A, 0.02 mol frac B, and 0.003 mol frac C. The design for this process needs to consider equipment sizes, energy costs, and process constraints to arrive at an economic optimum, but those details are not included here due to conserve space. The equipment sizing and costing are standard.

For purposes of this example, a three-stage multi-effect evaporator is used for water removal (assuming the evaporators to be falling film). The vapor generated by steam in the first stage is used as the heating medium in the second evaporator stage (operating at lower pressure). Liquid from the first evaporator is the feed to the second. Liquid and vapor flow similarly from the second to the third evaporator. The flow of liquid and vapor is co-current so that the lowest pressure and temperature are in the final stage. The liquid from the third evaporator feeds the first distillation column that separates A in the distillate from B and C in the bottoms. The second column separates B in the distillate from C in the bottoms.

Table 1 contains process conditions for the evaporators in this example, while Table 2 contains process data for the distillation columns.

Table 1 Process conditions in evaporators

Parameter	Value	Parameter	Value
E1 duty	584 kW	E3 liquid out	4.9 kmol/h
E1 liquid out	104 kmol/h	E3 temperature	101ºC
E1 temperature	122ºC	E3 pressure	0.15 atm
E1 pressure	2 atm	E3exit H2O	0.08 mol frac
E2 liquid out	54 kmol/h	E3 exit A	0.21 mol frac
E2 temperature	110ºC	E3 exit B	0.62 mol frac
E2 pressure	1.3 atm	E3 exit C	0.09 mol frac

4. ENERGY INTEGRATION

In this design, steam is used both in the column reboilers and in the first multi-effect evaporator and cooling water is used in the two column condensers. However, observation shows, and a pinch analysis (e.g. Seider *et al.*, 1999) confirms, that process conditions have been set so that the top column temperatures are both higher than the temperature in the first evaporator. Also, the sum of the two condenser duties exactly matches the evaporator duty (584 kW).

Table 2 Process conditions in columns

Parameter	Value	Parameter	Value
C1 cond duty	330 kW	C2 cond duty	254 kW
C1 th stages	8	C2 th stages	8
C1 feed	4 from bs	C2 feed	4 from bs
C1 pressure	0.8 atm	C2 pressure	0.15 atm
C1 top temperature	142ºC	C2 top temperature	159ºC
C1 dist	1.9 kmol/h	C2 dist	2.5 kmol/h
C1 dist mol frac	H2O=0.2 A=0.54 B=0.26	C2 dist mol frac	A=0.001 B=0.999
C1 base	3 kmol/h	C2 base	0.5 kmol/h
C1 bs mol frac	A=0.001 B=0.85 C=0.15	C2 bs mol frac	B=0.01 C=0.99

It therefore is feasible to integrate the design further by using the overhead vapor streams from both columns as the heating medium in the first evaporator (Figure 3). The liquid condensate must be kept separate by partitioning the evaporator chest so that the liquid condensed can go to separate reflux drums for each column. This integrated design reduces both steam and cooling water consumption and reduces capital by eliminating the need for individual column condensers. For companies that seek to minimize capital investment and reduce operating costs, this integrated design offers significant opportunities. The questions then focus on whether the design can run in actual operation.

At steady-state, the heat duties can be balanced exactly between the column condensers and the first evaporator. However, from the viewpoint of operability, important problems must be identified and solved: (1) can the system be started up and shut down safely, (2) can it produce consistent product quality, and (3) can it deal with changes in operating conditions (water content in crude feed, column reflux flows, etc.)? Westphalen *et al.* (2003) summarize some of the basic principles about the control of heat exchanger networks and ways to assess their controllability. Unless such questions are addressed prior to a finalized design, the process may never be able to run as designed.

In examining the plantwide control of any integrated process design, one of the key objectives is to provide mechanisms or manipulators that prevent disturbances from propagating around the material and energy loops. If necessary, the process design needs to be changed to make it more operable. Such changes need to be justified in terms of economics.

For example, one expected disturbance is a change in the water content of the crude evaporator feed. If the crude feed water concentration increases, then the liquid and vapor flows from the evaporators will change. The amount of water in the feed to the distillation columns will increase since there is not enough energy coming from the column overhead vapor streams. The disturbance will take much longer to disappear than with no energy integration as shown in Figure 4, where the evaporator is run open-loop with no adjustment to maintain a certain water concentration in the third stage (while the two columns are run in closed-loop) compared with the design with no energy integration.

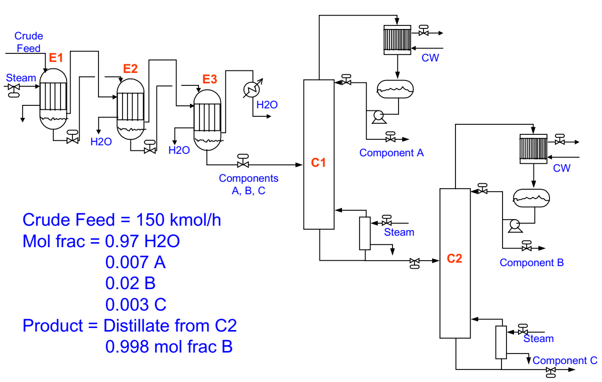

Fig. 2. Bio-process downstream example

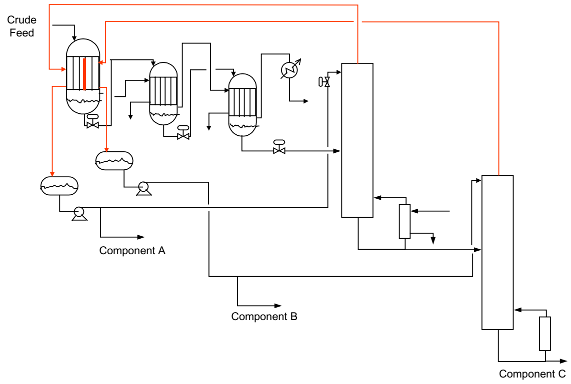

Fig. 3. Design with energy integration

5. CONTROL OF EVAPORATOR EXIT WATER CONTENT

The main goal for this system then becomes the control of the exit water content (as measured by temperature) from the third evaporator as the way to isolate disturbances. Heath *et al.* (2000) provide some discussion on the control of a single evaporator. The main alternative control strategies are:

(1) Bypass some of the crude feed to the third evaporator assuming that more energy comes from the column overhead streams than is required to remove the water content. If the water content increases in the exit stream, the bypass flow is decreased.

(2) Manipulate the crude feed flow and other liquid flows (going backwards). If the water content increases in the exit stream, the liquid flow from stage 2 to 3 is decreased, and so on.

(3) Underdesign the evaporators so that extra steam flow must always be added to the third evaporator. If the water content increases in the exit stream, the supplemental steam flow is increased.

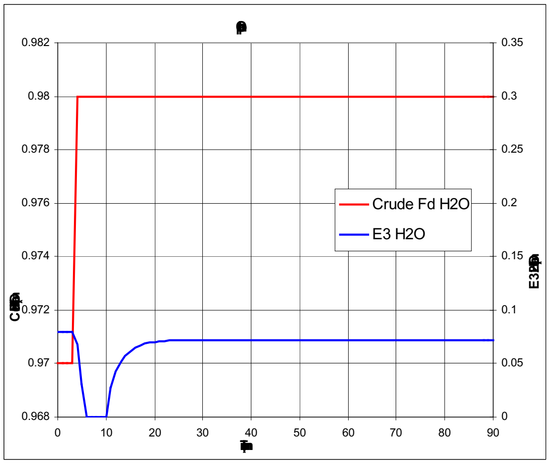

Fig. 4a. Open loop response to increase in feed water content with no energy integration

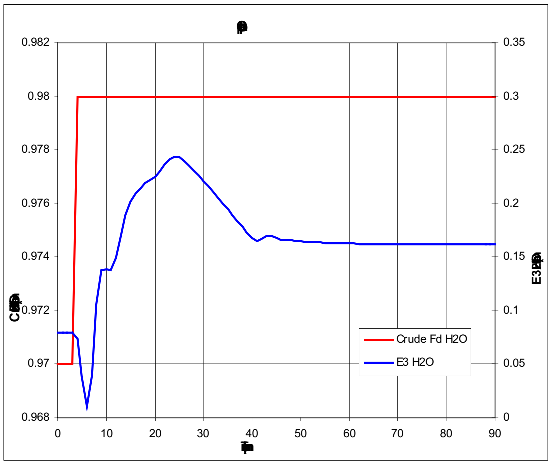

Fig. 4b. Open loop response to increase in feed water content with no energy integration

Each of these alternatives has some potential advantages and disadvantages that must be evaluated via dynamic analysis and simulation. A purely steady-state evaluation will not provide the complete picture. The details of this dynamic analysis cannot be presented here completely. One of the main responsibilities of a control engineer working in process development is to generate ideas for alternative control strategies and process designs and then to evaluate them based on dynamic performance and economics. The ideas come from a fundamental understanding and a quantitative assessment of the process (not from purely mathematical algorithms).

It turns out that the process design must have a manipulator to serve as the key break point for avoiding interaction between disturbances that affect the evaporators and columns. The nature of a fermentation process inherently causes variability in the feed composition to downstream units, adding to the importance of designing for control

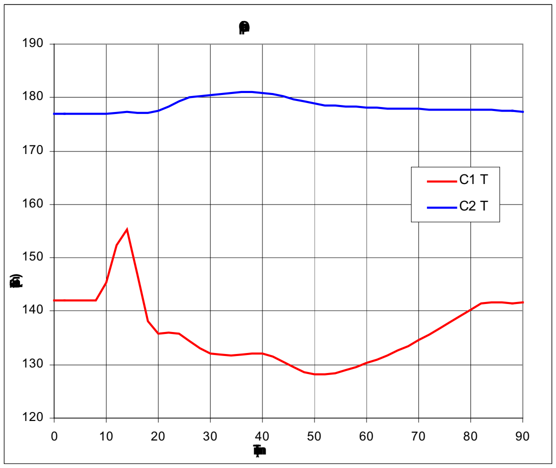

Fig. 4c. Open loop response to increase in feed water content with energy integration

6. DESIGN AND CONTROL

During abnormal situations, such as the loss of crude feed flow, the integrated design would create significant problems. Since the columns rely on the evaporators to condense their overhead streams, a loss of evaporator crude feed flow or other parts of the evaporator system would require an immediate shut down of the two distillation columns to prevent over-pressurization. This would cause the column contents to dump and means that the columns could not be run under total reflux conditions. Start up of the integrated system would be lengthened since crude feed is needed to bring up the columns, which would produce off-specification material until the desired temperature and composition profiles are achieved.

There are several alternative design changes that might potentially achieve some degree of greater independence between the evaporators and columns. One is to include auxiliary column condensers in parallel to the first evaporator stage, so that the columns could always be run on total reflux. This requires capital, which it was hoped could be avoided by using energy integration in the first place.

A second is to install the ability to feed make-up water into the first evaporator as a way to provide an energy sink. The water vapor generated in this way still must be removed and condensed, which means enough water must be fed to go through all three effects. This requires some additional capital, but much less than auxiliary condensers. It does, though, still rely on operation of the evaporation.

A third is to avoid the direct integration completely by generating steam with the column overhead streams. The steam would go into a header and supply the first evaporator stage. Excess steam would be vented or used elsewhere in the process and any deficiency in steam could be supplied from the plant steam source. The trade-off is the additional capital costs of the condensers and boilers with twice the heat transfer area (for the two temperature differences).

A fourth design alternative is to explore the value of a buffer tank between the third evaporator stage and the first column. A tank that is large enough would in principle filter out any possible changes in water concentration or in flow. This too requires extra capital and introduces inventory in a piece of equipment that adds no inherent value to the process.

Figure 5 shows the integrated system with one possible control strategy and design. Here the third stage evaporator temperature (water content) is controlled with the make-up steam flow to the third evaporator. Make-up water to the first evaporator is added in case the crude feed flow is lost. This could be done by override pressure controllers on the two columns. If the pressure in either column rises too much (indicating a loss of evaporator crude feed), then makeup water is added to the first evaporator stage so that the column overhead vapor streams can be condensed. The rest of the control strategy is also shown with the two column temperature controllers to maintain final product purity. Only a single temperature needs to be controlled in either column to maintain the desired composition profile and product purities. Ratios of reflux to feed flow can be used if more direct control of composition is needed.

Figure 6 shows the closed-loop dynamic response to a change in crude feed water content with this control strategy. These results come from a rigorous nonlinear dynamic simulation of the entire evaporator and distillation system. The increase in the feed water concentration is handled by adjusting the steam flow to the third evaporator. This results in a fairly minor disturbance for the column temperature controllers and disappears more quickly than the case where the evaporator was run open-loop with no control of exit water content. Similar analysis can be done with other design and control alternatives.

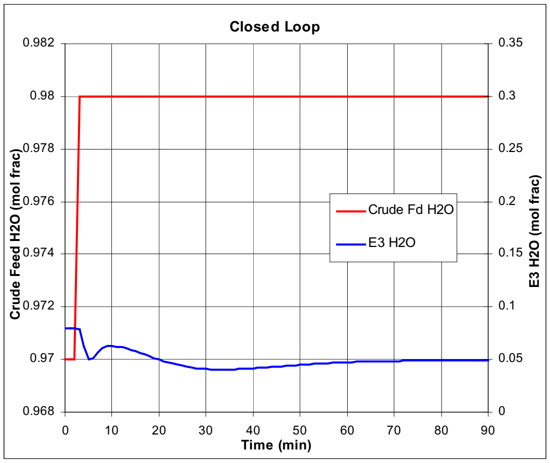

Fig. 6a. Closed loop response to increase in feed water content with control of exit evaporator water

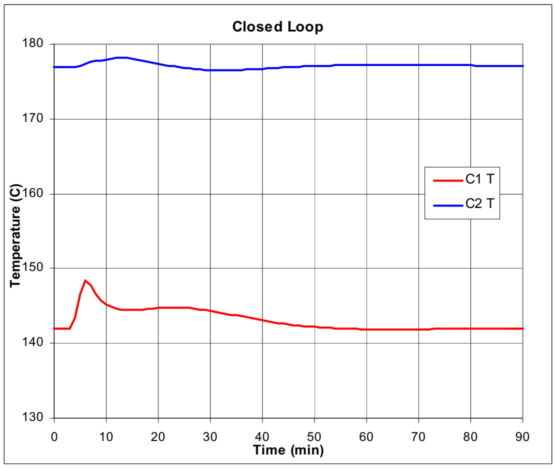

Fig. 6b. Closed loop response to increase in feed water content with control of exit evaporator water

7. CONCLUSION

This paper has presented an industrial view on the design and control of energy integration for bio-processes where evaporation and distillation are used for water removal and product purification. Such challenges will arise as new chemical processes are developed and commercialized using renewable feedstocks to manufacture chemicals and other materials. Because a fermentation process will inherently create disturbances in the feed composition to downstream units, controllability must be examined at the design stage, particularly with increased energy integration. This also highlights the large incentive to develop alternative separation processes that require less energy than evaporation or distillation.

The main objective for control of systems that interact with both energy and material flows is to provide mechanisms or manipulators to prevent disturbances from propagating. In the example discussed in this paper, this meant controlling the water concentration from the last evaporator stage before it reaches the distillation columns. If necessary, changes to the process design must be made to ensure the system is controllable.

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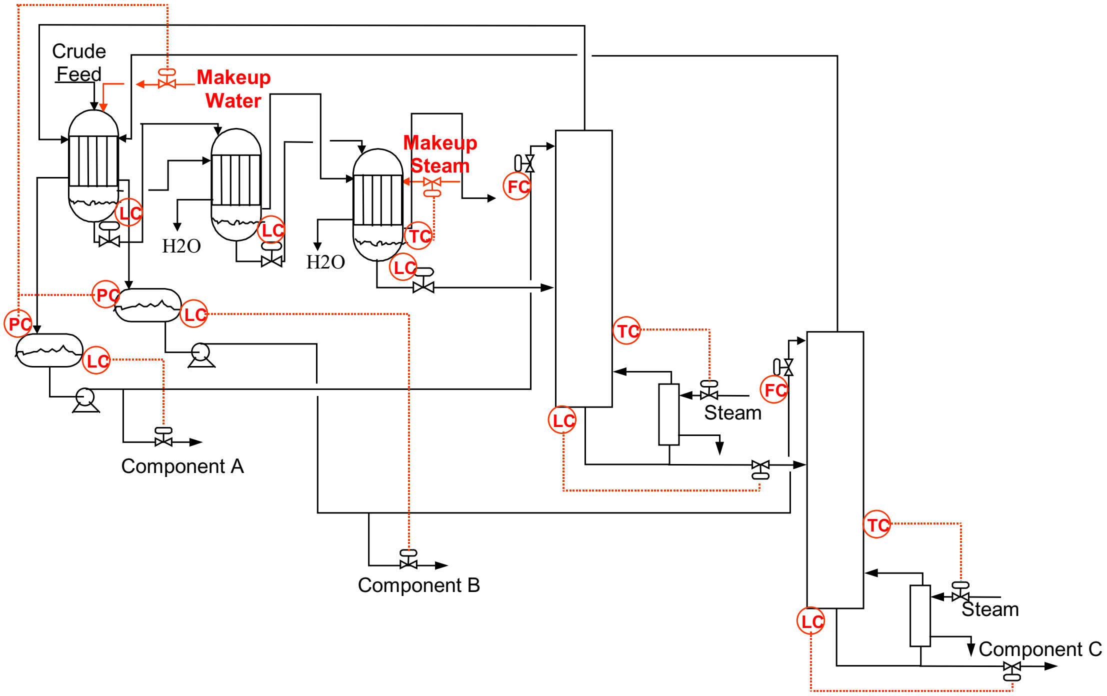

Fig. 5. One possible design and control strategy for integrated design