Control and Dynamics of a Distillation Column with Heat Pump

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Abstract

The main reason for using a distillation column equipped with a heat pump to integrate the reboiler and cooler duty is to save energy and thus reducing operating costs. In this paper we compare the effect on economics and control properties for a single column and a column integrated with a heat pump. Separation of products from an ethanol fermentation process is used as a case study.

1. Introduction

Integrated processes are often relatively difficult to control. Usually they give large interactions and require non-conventional control structures.
In control structure design the controlled variables, manipulated variables, measurements and links between them are selected. Good control structure is the basis for avoiding instability and operational problems. Good steady state economic performance of the structure is unobtainable if dynamic properties are not suitable. When separating components in a distillation column there are always many alternative structures to select among. The main goal is to minimise the amount of energy or total annualised costs. One possible structure is based on a heat pump, which integrates the column condenser with its reboiler. This alternative promises big savings on operating costs compared with conventional columns. Many authors have studied heat pumps in different combinations with distillation columns. Their main goal has been to reduce the energy consumption. Nielsen et al. (1987) studied a pilot plant distillation column equipped with heat pump and showed positive feed back from the column top to the reboiler through the heat

pump. Nielsen et al. (1988) studied the experimental results from multivariable adaptive control of a distillation column with heat pump. Meili (1990) showed respectable cost reduction on cases of isopropanol-water, ethylbenzen-styrene and propane-propylene. Björn et al. (1991) compared different heat pump configurations and distillation columns. Koggersbøl et al. (1996) analysed how the stability properties of a distillation process changed upon heat integration with an indirect heat pump. Salim et al. (1991) focused their developed algorithm on the condenser and evaporator heat loads and the coefficient of performance of the heat pump. We here want to compare the steady-state economic and control behaviour for a single column and a column integrated with a heat pump.

2. Case study

The example is based on the separation of ethanol and water, from the ethanol fermentation process (CACHE, 1988). The feed containing water (97 %) and ethanol (3 %) should be separated to obtain an azeotropic mixture of ethanol (87.4 %-purity) at the top of the column and water (99 %-purity) in the bottom.

2.1. Single column

A single column is shown in figure 1.

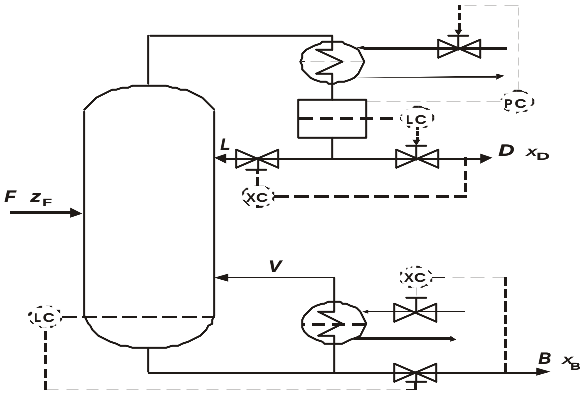

Figure 1 Single column

The model of the system is based on energy, material and component balances. Phase equilibria are calculated by the Wilson equation; vapour flow rates depend on the pressure differences over the trays; linearised liquid dynamics are used (Engelien et.al.(2002)). A single column has five degrees of freedom (reflux flow rate (L), boil-up flow rate (V), distillate flow rate (D), bottom product flow rate (B), condensed flow rate (V_d).

$$u^T = [\, L\ V\ D\ B\ V_d] = [6.84\ 8.96\ 1.42\ 59.9\ 8.26] \quad (1)$$

All flow rates are given in kmol/min. Two liquid holdups (reboiler and reflux drum) need to be stabilised and have no steady-state effect, so there are three steady-state degrees of freedom left. Disturbances are the feed flow rate (F) and feed composition (z_F):

$$d^T = [\, F\ z_F\,] = [\, 61.33 \pm 12.27 \text{ kmol/min } 0.03 \pm 0.01 \text{ kmol/kmol}] \quad (2)$$

There are constraints related to product purities and pressure in addition to non-negative flow rates:

$$\begin{aligned} &x_b \leq 0.01 \\ &x_d \geq 0.874 \\ &0.5 \text{ bar} \leq p_b \leq 3.5 \text{ bar} \end{aligned} \quad (3)$$

The operating costs depend on the steam duty (Q_b), cooling water duty (Q_c) and product flows (F, B, D). The economic objective is to maximise the profit. When the feed flow rate is given and only minor changes in product flow rates are allowed due to high purity specifications, this can be simplified to minimise the energy costs. If we assume free cooling water, this is equal to minimising the steam duty ($J = Q_b$). At optimum both product purity constraints and the upper pressure constraint are active at optimum. We track the optimal operation by controlling the variables at active constraints, and we control the pressure, top and bottom composition. Nominally the steam duty (Q_b) is 6.06 MW and the cooling water duty (Q_c) is 5.59 MW. To stabilise the process the condenser holdup is controlled by the distillate flow rate, the reboiler holdup is controlled by the bottom product flow rate and the pressure is controlled by the cooling water flow rate. To achieve acceptable control performance the distillate composition is controlled by the reflux flow rate, and the bottom product composition is controlled by the reboiler flow rate.

2.2. Integrated column

For the integrated column a heat pump integrates heat flow rates of the reboiler and condenser (see figure 2). The refrigerant circulating in a heat pump circuit removes heat in the condenser (with low temperature and pressure) and is evaporated. In the compressor the vapours are compressed to higher pressure and temperature. The pressurised and hot vapour is condensed in the column reboiler. Through the expansion valve the refrigerant is vaporised to lower pressure. The circle repeats.

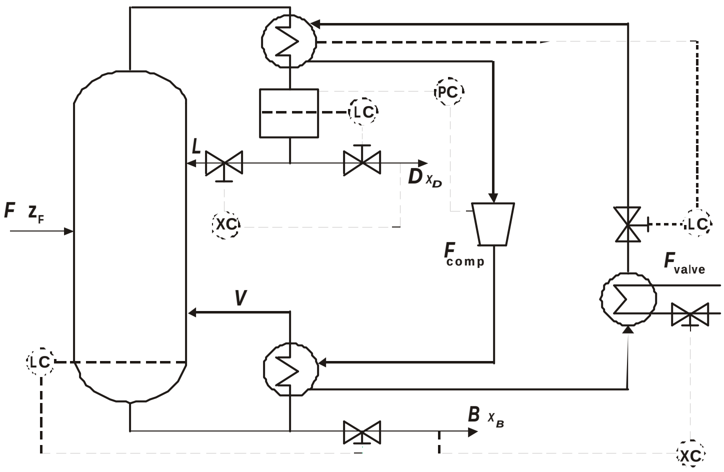

Figure 2: Integrated column – column integrated by heat pump.

A simple heat pump model that consists of one compressor, one expansion valve, one condenser, one reboiler, one extra cooler and two storage tanks is used. The integrated column has six degrees of freedom (reflux flow rate (L), distillate flow rate (D), bottom product flow rate (B), compressor work (W_{comp}), expansion valve flow rate (F_{valve}), extra cooling water flow rate (F_{cw})).

$$u^T = [L\ D\ B\ W_{\text{comp}}\ F_{valve} F_{\text{cw}}] = [6.84\ 1.42\ 59.9\ 0.71\ 9.60\ 9.84] \qquad (4)$$

All flow rates are in kmol/min and the compressor work is in MW. Three liquid levels (in reboiler, reflux drum and refrigerant level in condenser) need to be stabilised and have no steady-state effect, so there are three steady-state degrees of freedom left. The disturbances and constraints are the same as for the single column. The operating costs depend on the cooling water duty (Q_{cw}), compressor work (W_{comp}) and product flows (F, B, D). The economic objective is to maximise the profit and as for the single column this can be simplified to minimise the cost of energy ($J = P_{\text{el}}W_{\text{comp}} = 5W_{\text{comp}}$). We here assume that the electricity costs five times as much as the steam. As for the single column the purity constraints and upper pressure constraint are active at optimum, and we select to control the pressure, bottom composition and top composition. Nominally the cooling water duty (Q_{cw}) is 0.2477 MW and compressor work (W_{comp}) is 0.713 MW. The energy costs for the integrated column (J = 3.56) are reduced with 41 % compared to the single column. To stabilise the process we need to control the column pressure, reboiler holdup, condenser holdup and heat pump holdup. As for the single column the condenser holdup is controlled by the distillate flow rate and the reboiler holdup is controlled by the bottom product flow rate. The heat pump holdup is stabilised by controlling the smallest tank holdup in the heat pump system by manipulating on the flow rate in the expansion valve. The pressure is controlled by the compressor work. The compressor work has significant larger effect on the pressure than the other manipulated variables have. A step in the compressor work gives an inverse response in the pressure response and limits how fast the pressure can be controlled. To achieve acceptable control performance the distillate composition is controlled by the reflux flow rate, and the bottom product composition is controlled by the cooling water flow rate to the extra heater in the heat pump.

2.3. Simulations

Single column and integrated column controllers were designed by using IMC-tuning and compared by doing steps in the feed flow rate and feed composition. Figure 3 shows the responses for pressure, top composition and bottom composition for a 20% increase in the feed flow rate. Figure 4 shows the responses for the pressure, top composition and bottom composition for an increase in the feed fraction (from 0.03 to 0.04).

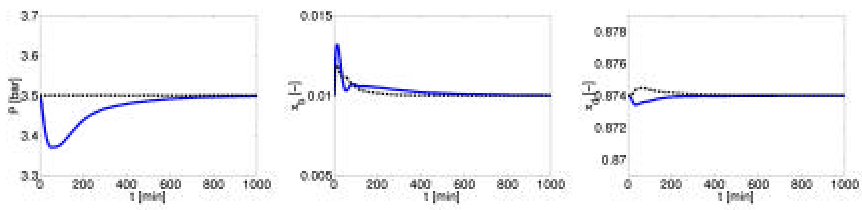

Figure 3: Responses for pressure, bottom and top composition for the integrated (solid) and the single (dash-dot) column for a 20% increase in the feed flow rate.

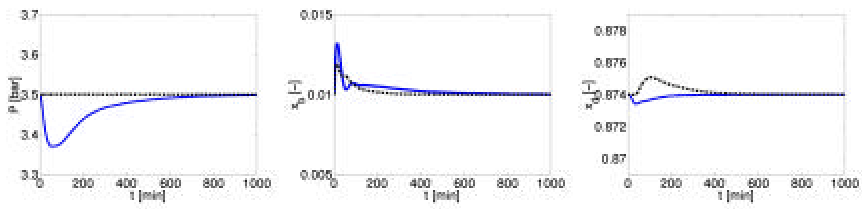

Figure 4: Responses for pressure, bottom and top composition for the integrated (solid) and the single (dash-dot) column for a increase in the feed composition (from 0.03 to 0.04).

For composition control there are only minor differences between the control performance for the single and integrated column. Pressure control performance is significantly better for the single column than the integrated column. The reason is that the upper bandwidth for the pressure controller is limited of the inverse response between the pressure and compressor work. Anyway, there is no problem to stabilise the pressure, and the extra cost connected to move away from optimum to avoid violating the pressure constraint for the integrated column is rather small. The energy costs for the integrated column at 3.3 bar is reduced by 40 % compared to the single column at 3.5 bar.

3. Conclusions

A column integrated with a heat pump reduces the operating costs compared to a single column (when the cost of electricity is not too large compared to the cost of steam). For composition control there are only minor differences in performance between the single and the integrated column. The pressure control is significantly slower and gives larger control error for the integrated column than for the single column. However, it is easy to stabilise the integrated column, and the increase in energy costs connected to move away from optimum to avoid violating the pressure constraint is negligible.

4. References

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