Quantitative Comparison of Alternative Control Schemes for Air-Cooled Condensers

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DOI 10.1002/aic.10648
Published online September 28, 2005 in Wiley InterScience (www.interscience.wiley.com).

Air-cooled heat exchangers present unique control problems because they are more sensitive to ambient disturbances than water-cooled heat exchangers. Each of the several alternative methods for manipulating heat removal has some disadvantages. The obvious choice of manipulating the flow rate of the air is mechanically difficult. This investigation compares three alternative process and control structures for controlling pressure in a distillation column with an air-cooled condenser: manipulating air flow (fan speed, louver opening, or blade pitch), throttling a control valve in the overhead vapor line, or bypassing vapor around the condenser. Results show that direct manipulation of air flow rate is slower than other methods, and the deviations in column pressure are larger. Overhead vapor throttling gives good control of column pressure, provided the nonlinearity of the butterfly valve is taken into account and the dynamics of the large valve are not too slow. However, reflux-drum pressure and temperature vary drastically. This necessitates the use of a high-head reflux pump and results in varying degrees of subcooling, which affect the separation in the column. Hot-vapor bypassing, using two control valves (one in a vapor bypass line controlling reflux drum pressure and one in the vapor line to the condenser controlling column pressure), provides effective pressure control and lessens the variability in reflux-drum temperature. However, more condenser area is required and the plumbing must be correct so that hydraulic problems do not occur. *AIChE J,* 52: 611–622, 2006
Keywords: process control, air cooling, condenser control

Introduction

The majority of condensers in distillation columns are cooled by cooling water. Lower reflux-drum temperatures are achievable than when air-cooled condensers are used because of the difference between the dry-bulb and wet-bulb temperatures. The resulting lower column pressure reduces energy consumption in many systems. In addition the heat-transfer area is somewhat smaller with water cooling because of the much lower air-side film coefficient with air cooling. Mueller[1] presents a clear discussion of the advantages and disadvantage of air cooling and summarizes design methods. Smith[2] gives typical overall heat-transfer coefficients in air-cooled heat exchangers for a variety of types of systems. Shinskey[3] provides a qualitative discussion of the control effectiveness of several alternative systems. The purpose of this report is to quantify these issues.

Water-cooled condensers

The pressure in most distillation column is controlled by the rate of condensation in the condenser. In water-cooled condensers, there are several methods used.

(1) Manipulation of the flow rate of the cooling water.

(2) Direct pressure control of the column using a valve in the overhead vapor line before the condenser.

(3) Manipulation of a control valve at the outlet of the

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condenser ("flooded" condenser). The heat transfer is changed by changing the area available for condensation.

(4) Addition of an inert gas and use of a "vent/bleed" system.

(5) Use of a "hot-vapor bypass" line around the condenser to the top of the reflux drum

All of these methods have advantages and disadvantages. The first is probably the most straightforward and widely used. However, in some plants throttling cooling water flow rate is undesirable because fouling problems arising from low velocity can allow the depositing of solids in the cooling water. It also can create corrosion problems because the exit cooling water temperature can become too high, particularly in cold weather operation when cooling water flow rates are low.

The second method is seldom used in large columns because a large butterfly valve in the vapor line is required. Butterfly valves sometimes have nonlinear valve characteristics, which can complicate controller tuning. Their dynamic response is sometimes quite slow because of their size. The method also has the problem of variable pressure (and temperature) in the reflux drum, which presents two problems. First, the reflux pump/valve must be sized to handle large changes in the pressure differential between the column and the reflux drum. Second, the reflux is subcooled to varying degrees, which affects the "internal reflux" and thus the separation.

The third method floods the condenser with liquid, which changes the area of heat transfer for condensation. The dynamics of this type of system can be quite slow because of the time required to cover or expose tubes. The response can also be nonlinear because of different rates of lowering and raising the liquid level.

The fourth method introduces another component into the system that could affect product quality. Some product will also be lost in the vent stream. The reflux is also subcooled to varying degrees as conditions change.

The fifth method requires the installation of a bypass line with a control valve around the condenser to the top of the reflux drum. A second valve is installed either before or after the condenser. The line from the condenser should discharge near the bottom of the reflux drum. The hot vapor enters at the top of the drum, and the subcooled liquid enters near the bottom under the liquid surface. There is heat transfer and condensation at the liquid–vapor interface in the drum. This system requires careful attention to the physical layout of the plumbing.

If reflux-drum temperatures are high, steam can be generated in the condenser. Then column pressure is controlled by manipulating the setpoint of a steam pressure controller, and boiler feed water is brought into the steam side of the condenser to control the level of water.

Air-cooled condensers

The pressure control schemes used with water cooling can be applied with air cooling. All of the schemes, with the exception of the first, are essentially independent of whether water or air cooling is used. However, the sensitivity of the system to ambient changes in temperature is much greater in air-cooled heat exchangers. The famous "blue northers" that hit plants in the Gulf coast region (rapid drop in temperature as a cold front sweeps through) and rain storms greatly affect not only air temperatures but also heat-transfer coefficients (air-side film coefficient changes drastically). So processes with air-cooled heat exchangers must have control systems that can effectively compensate for these rapid ambient disturbances. The principal disturbance used herein is a drop in inlet air temperature from 305 to 294 K.

The first method of pressure control listed above is significantly different in air-cooled heat exchangers because it is more difficult to manipulate the flow rate of the air. To manipulate cooling water, a control valve is installed in the cooling water line coming from a cooling water header at high pressure. A similar setup with air would be very impractical because of the need to compress large quantities of air. Therefore some other method must be used to change the air flow rate if this scheme is used.

Typical air-cooled heat exchangers have fans either below the tubes (forced air) or above the tubes (induced air) in the condenser. Finned tubes are used to increase the area on the air side. They are typically arranged in banks of horizontal tubes. Louvers can be installed above or below the condenser. In some designs it is also possible to recirculate hot air leaving the heat exchanger back to the fan inlet. There are four ways to change the air flow rate.

(1) Change fan speed.
(2) Change the pitch of the blades on the fans.
(3) Change the position of the louvers.
(4) Change the recirculation rate.

None of these alternatives is mechanically simple. They are often unreliable and can exhibit poor sensitivity (difficult to make small changes). Therefore other methods for changing heat removal are frequently used in air-cooled heat exchangers.

Shinskey[3] provides a very lucid discussion of the control problems associated with all of these schemes. He recommends the use of the bypass scheme, using two control valves. The first valve is in the inlet vapor line to the condenser and controls column pressure (back-pressure controller). The second valve is in the vapor bypass line and controls the pressure in the reflux drum (downstream pressure controller).

Shinskey does not recommend the use of "flooded condenser" operation with a valve *after* the condenser. The horizontal tubes are typically arranged "with only two to four rows of tubes oriented vertically, so that flooding does not give smooth control." This occurs because the heat-transfer area is a nonlinear function of the amount of liquid in the condenser.

This article presents a quantitative comparison of three alternative schemes for controlling pressure in a distillation column with an air-cooled condenser.

Process Considered

The numerical example is a depropanizer column separating propane and *n*-butane. Figure 1 shows the flowsheet conditions for the case with a valve in the overhead vapor line controlling column pressure.

The feed composition is 50 mol % propane and 50 mol % *n*-butane. Feed flow rate is 908 kmol/h. The column has 30 trays (32 stages using Aspen terminology), and the feed is fed in the middle of the column.

A reflux-drum temperature of 325 K is assumed in this process with the air-cooled condenser. This should be compared with a typical reflux-drum temperature of 316 K in

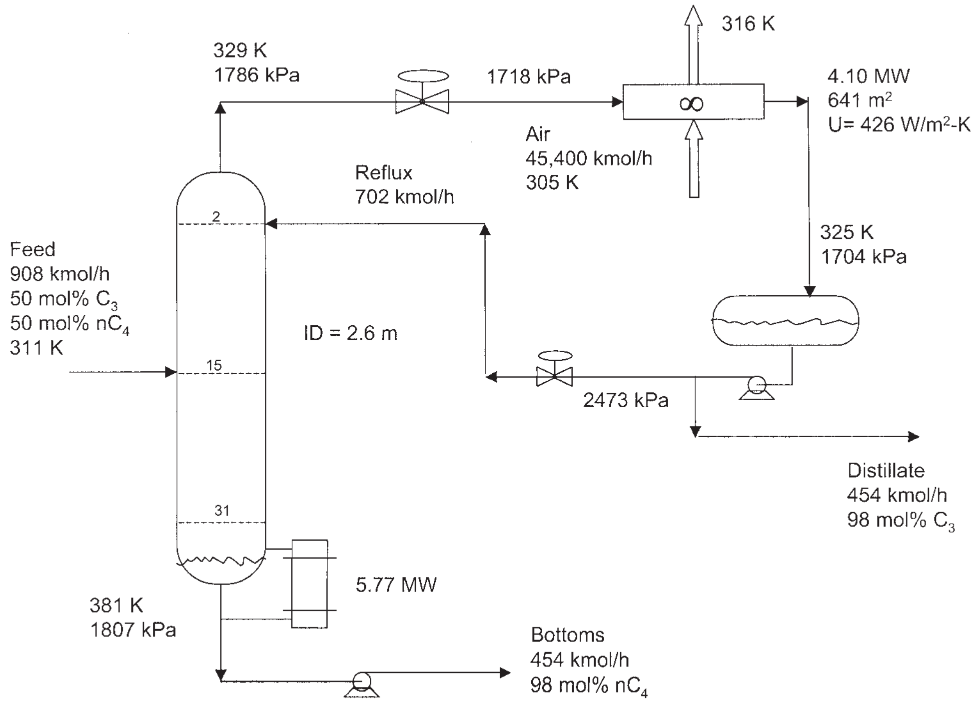

Figure 1. Flowsheet of air-cooled condenser with vapor valve.

water-cooled condensers. The higher reflux-drum temperature is dictated by the smaller overall heat-transfer coefficient in air-cooled heat exchangers. A value of 426 W m^{-2} K^{-1} is recommended by Smith[2] for condensing light hydrocarbons. The distillate composition is 98 mol % propane, so the reflux-drum pressure is 1704 kPa at 325 K and this composition. The bottoms composition is 98 mol % *n*-butane. The reflux ratio is 1.5. Reboiler heat input is 5.77 MW.

The valve in the overhead vapor line is designed for a 68.7 kPa pressure drop with the valve half open. The pressure drop through the condenser is 13.7 kPa. The reflux pump is design to provide a 2473 kPa discharge pressure so that the changes in reflux-drum pressure can be handled. Note that the reflux is subcooled, so the internal reflux ratio is higher than that of the external.

The air-cooled condenser is modeled in Aspen Dynamics as a countercurrent heat exchanger. An air inlet temperature of 305 K is assumed, and air flow rate is set at 45,400 kmol/h, which gives an exit air temperature of 316 K with a heat-transfer rate of 4.10 MW. The required heat-transfer area (tube wall) is 641 m^2. Of course the fin area is much larger. Assuming 0.0254 m diameter tubes, 9.14 m in length, requires 878 tubes with a volume of 4.08 m^3 and a mass of metal of 7763 kg. These parameters are used to set the dynamic feature of the heat exchanger (volumes of hot and cold sides and the equipment heat transfer in the Aspen Dynamics simulation).

Reflux-drum and base holdup volumes are set to give 5 min of holdup when the liquid levels are 50% of the total. The column diameter is calculated using Aspen Plus "Tray Sizing" to be 2.6 m.

Direct Column Pressure Control with Vapor Valve

The steady-state simulation of the depropanizer column in Aspen Plus is exported into Aspen Dynamics. The "Implicit Euler" integration algorithm and the "Standard" nonlinear solver options were found to provide the most stable and reliable dynamic simulations.

The control scheme shown in Figure 2 is installed. The features of this control structure are:

(1) The air flow rate is fixed.

(2) Column pressure is controlled by manipulating the valve in the overhead vapor line.

(3) Reflux-drum level is controlled by manipulating reflux flow rate.

(4) Distillate flow rate is ratioed to reflux flow rate.

(5) Base level is controlled by manipulating bottoms flow rate.

(6) Stage 25 temperature is controlled by manipulating reboiler heat input.

(7) Feed is flow controlled.

The level controllers are proportional with gains of 2. The temperature control loop has a 1-min dead time and is tuned using the relay-feedback test and Tyreus–Luyben settings (K_C = 0.77 and τ_I = 9.2 min with a temperature transmitter span of 55.6 K and set point of 363 K).

The pressure controller is the key loop in this system. The potentially slow dynamics of the large butterfly valve could adversely affect performance. To explore this issue, two values of loop dynamics are studied. In the first case a 0.25-min dead time and a 0.25-min first-order lag are inserted in the pressure controller loop. In the second case, these are both increased to 0.5 min. Pressure transmitter span is 687 kPa. The pressure controller is tuned for as tight pressure control as possible without excessive oscillation. The Ziegler–Nichols tuning rules are used when possible, but in some cases detuning is required for stable operation. The controller settings used are Ziegler–Nichols: K_C = 20 and τ_I = 5 min in the first case and K_C = 6.9 and τ_I = 3 min in the case with slower dynamics.

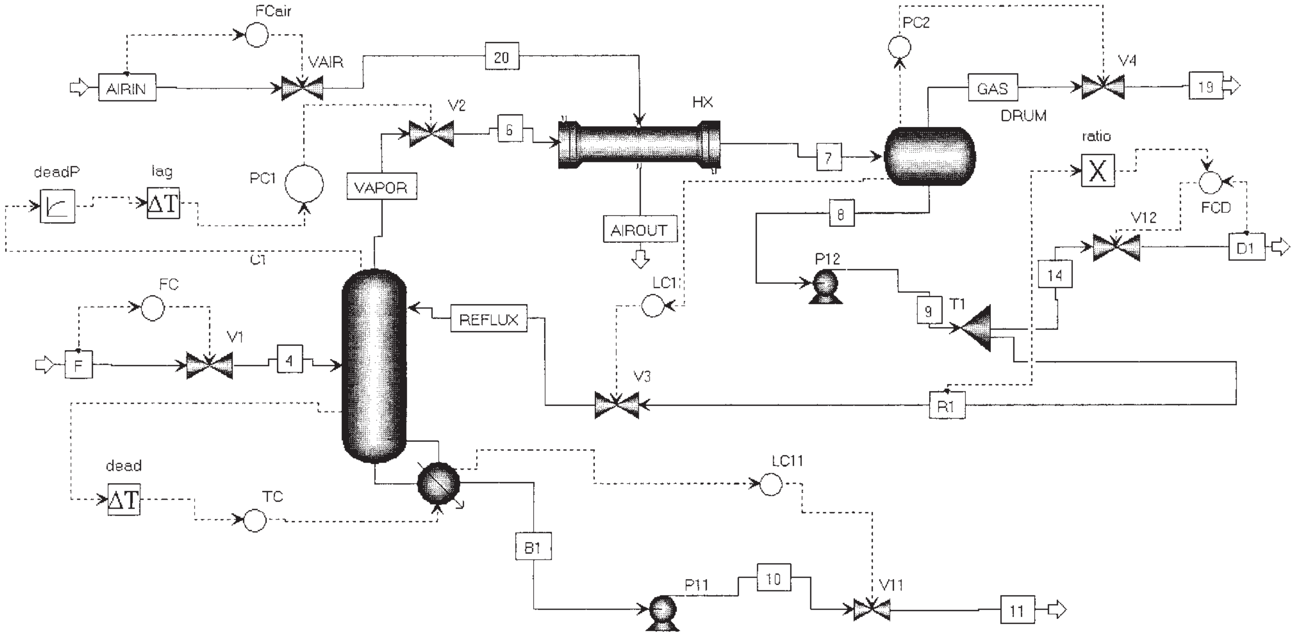

Figure 2. Control structure with vapor valve.

Figure 3 gives a direct comparison of the two cases. The disturbance is a step decrease in the inlet air temperature from 305 to 294 K at time equal 0.2 h. The slower valve dynamics produce a larger deviation of column pressure *PC* and a longer time to recover back to the set point pressure. Clearly it is important to use a fairly fast butterfly valve.

The issue of nonlinear valve characteristics should be mentioned at this point. As Buckley[4] has discussed, valves have several types of characteristics. Valve nonlinearity could adversely affect controller performance. However, the nonlinearity can be easily compensated for by the use of a nonlinear element that yields a linear relationship between valve area and the signal to the valve. This element can be inserted between the controller and the valve, or it may be an integral part of the valve positioner.

Figure 3 also shows the other problems associated with this

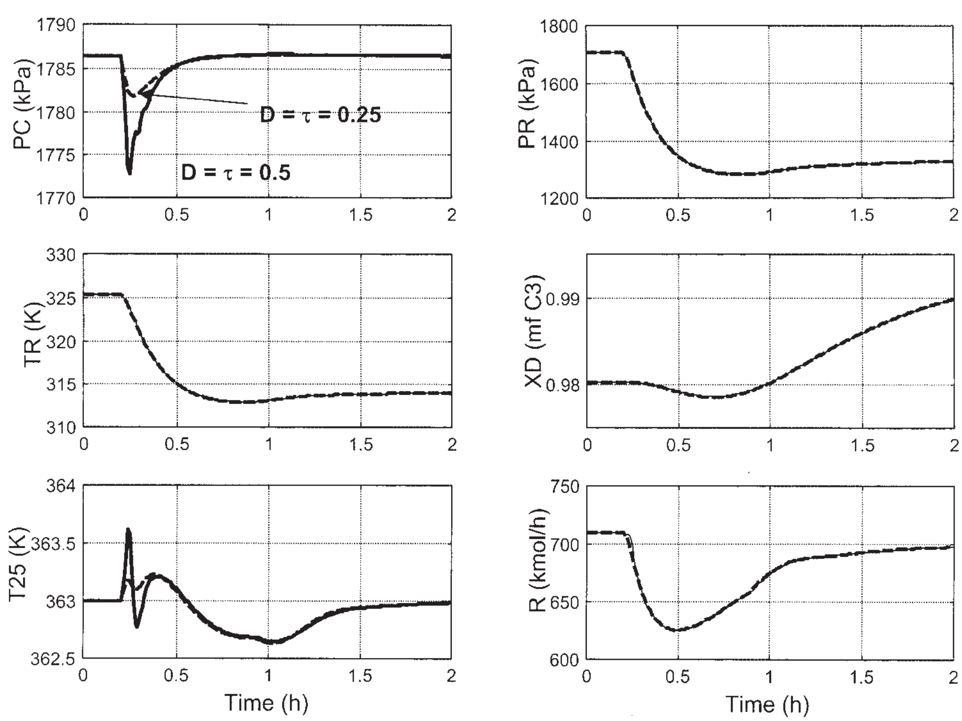

Figure 3. Vapor valve with different dynamics.

Air inlet 305 to 294 K.

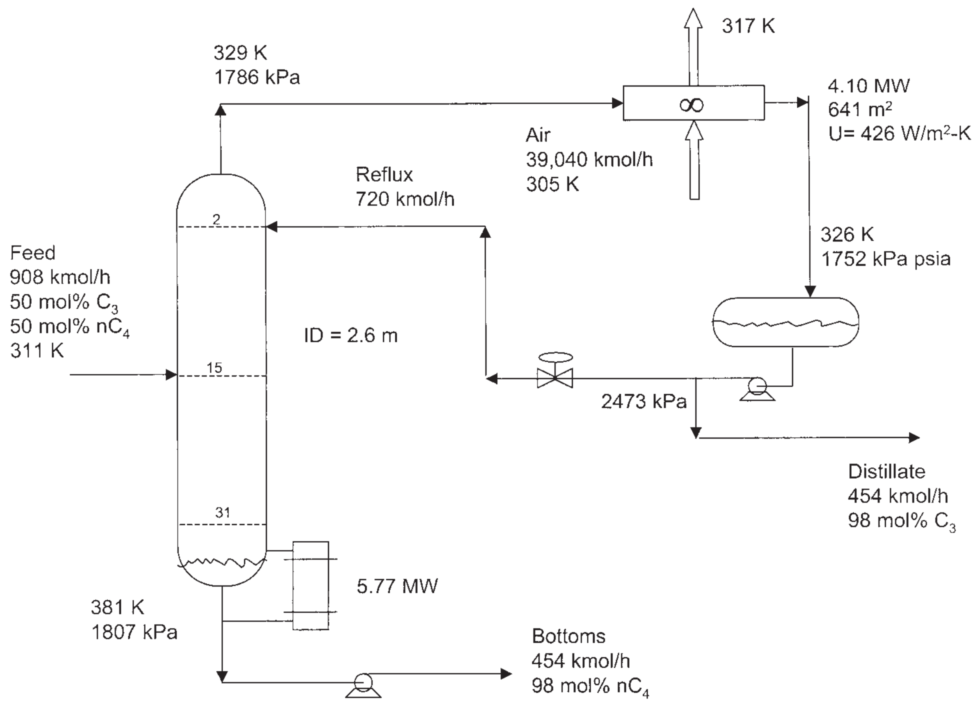

Figure 4. Flowsheet of air manipulation.

structure. The pressure in the reflux-drum *PR* drops from 1704 to 1305 kPa as a result of the lower air temperature. This requires a large change in the pressure drop over the reflux valve to get reflux back into the column at 1786 kPa.

The reflux is more subcooled with the drum temperature *TR* dropping from 325 to 314 K. The internal reflux increases for the same external reflux flow rate *R*, which the control structure produces, since the reflux ratio is held constant and the steady-state distillate flow rate is almost unchanged for this disturbance. The larger internal reflux is indicated by the increase in the distillate purity x_D from 98 to 99 mol % propane.

Air Flow Rate Manipulation

If the air flow rate can be changed, the valve in the vapor line can be removed (or opened wide). For the same column pressure of 1786 kPa, the reflux-drum pressure increases to 1752 kPa, which raises the temperature to 326 K. With the same size condenser, the air flow is reduced to 39,040 kmol/h, and the air exit temperature is 317 K. Figure 4 gives flowsheet conditions. Notice that the reflux flow rate has increased from 702 to 720 kmol/h to achieve the same product purities. This higher reflux ratio is attributed to the higher reflux-drum temperature (less subcooling).

A 0.5-min dead time and a 0.5-min first-order lag are inserted in the pressure loop. Relay-feedback tests are run and both the Ziegler–Nichols and Tyreus–Luyben tuning methods give oscillatory response. Empirical detuning leads to controller settings of $K_C = 1.5$ and $\tau_I = 10$ min.

Figure 5 gives the Aspen Dynamics flowsheet with the modified control structure where column pressure is controlled by manipulating air flow rate. In the simulation this is shown using a control valve, but in reality one of the mechanisms for changing air flow would be used. Figure 6 compares the performance of this system with the vapor-valve system. The disturbance is a drop in air inlet temperature. The air-manipulation scheme (dashed lines) produces much larger changes in column pressure and the dynamics are slower.

However, the pressure in the reflux drum changes very little, so reflux pump pressure head requirements are lower. The problems of variable subcooling are also eliminated. As shown in Figure 6, the distillate composition changes very little for the same external reflux flow rate.

Hot-Vapor Bypass

The final system studied is the bypass structure with a small amount of vapor flowing from the overhead vapor line upstream of the large vapor valve through a second smaller valve to the top of the reflux drum. The pipe containing the condensate coming from the condenser should discharge under the liquid surface near the bottom of the reflux drum. Thus there is hot vapor (329 K) coming directly from the column in the vapor space of the drum. The colder condensate (320 K) coming from the condenser flows into the bottom of the drum. The mixed temperature is 322 K under steady-state conditions with a bypass flow rate of 17.8 kmol/h. See Figure 7.

An interesting aspect of designing this system in Aspen Plus is setting the specification on the heat exchanger. The flow rate of the bypass vapor is set at 1.5% of the total vapor, and the drum temperature is set at 322 K and pressure at 1580 kPa. Then the exit temperature of the hot stream leaving the condenser is varied until the heat input in the drum is zero (adiabatic operation of the drum). The required temperature is 320 K.

A larger condenser is required in this system. The heat-transfer area is 818 m^2. Notice that the reflux flow rate (687

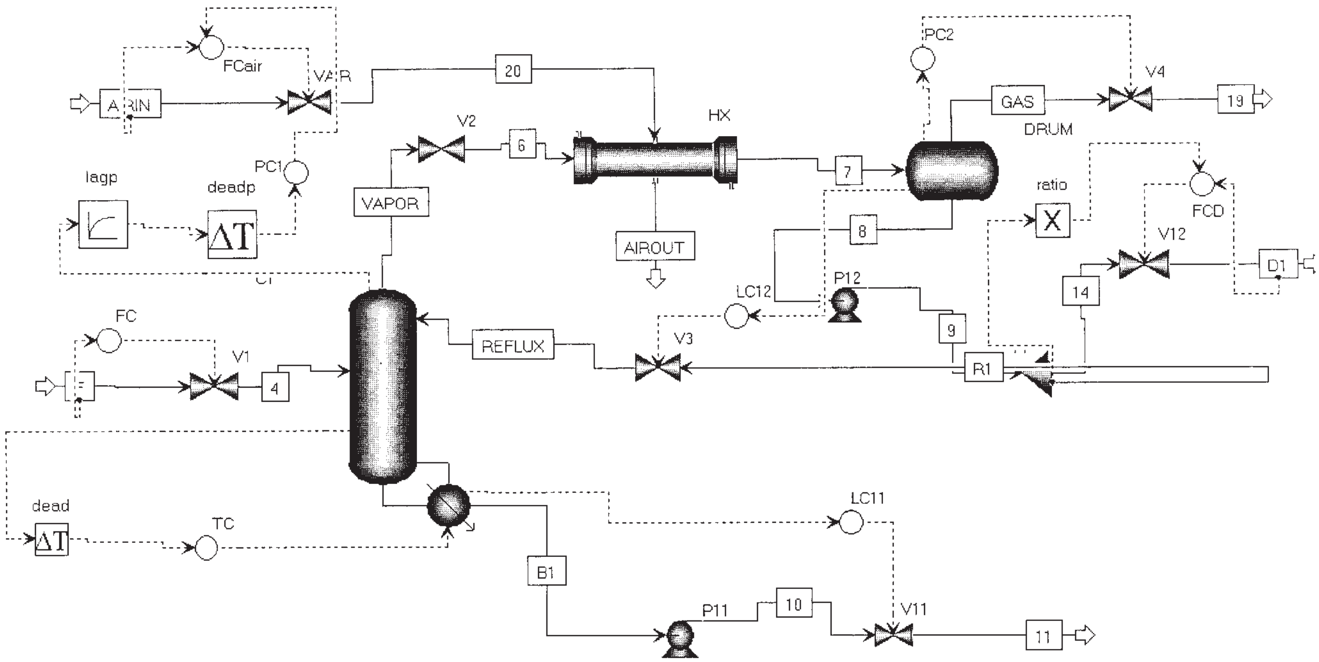

Figure 5. Control structure with air manipulation.

kmol/h) to achieve the same product purity is lower than that in the other cases because the reflux subcooling is greater.

Figure 8 shows the control structure. Column pressure is controlled by the vapor valve. Reflux-drum pressure is controlled by the bypass valve. Because the latter is a small valve, no lags are used in this pressure loop. Nominal settings of $K_C = 5$ and $\tau_I = 12$ min are used with a 687 kPa pressure transmitter span. The column pressure control loop has a 0.5-min dead time and lag. Ziegler–Nichols tuning gives oscillatory response. Tyreus–Luyben tuning is used: $K_C = 5.6$ and $\tau_I = 6.6$ min.

The positions of the three important control valves at design conditions are shown in Figure 7. Notice that the bypass valve is designed to be only 14% open under steady-state conditions.

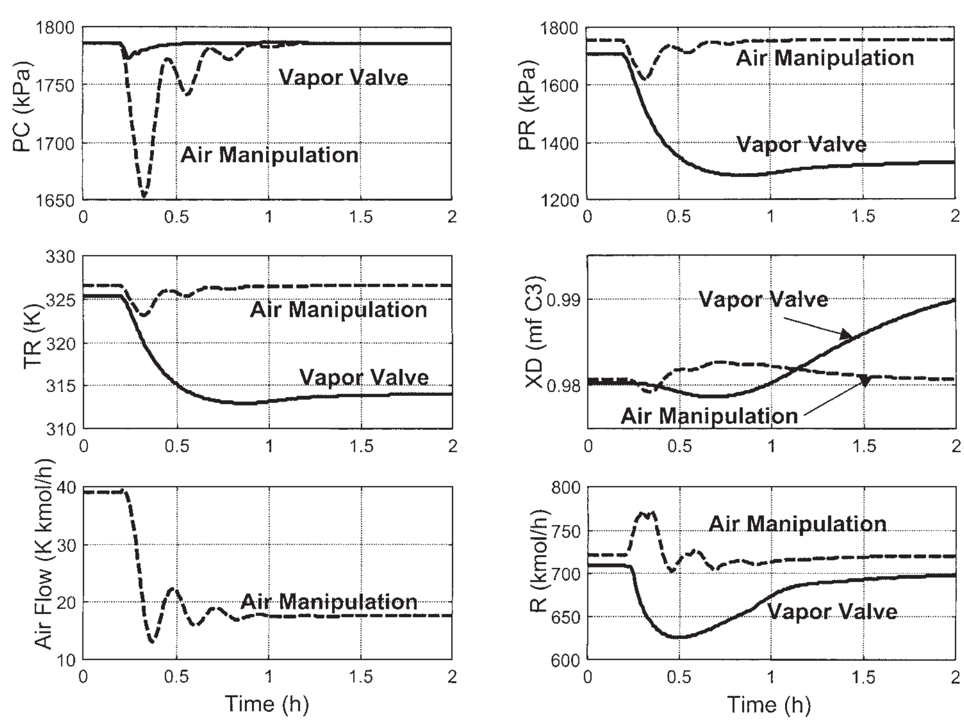

Figure 6. Comparison of vapor valve and air manipulation.

Air inlet 305 to 294 K.

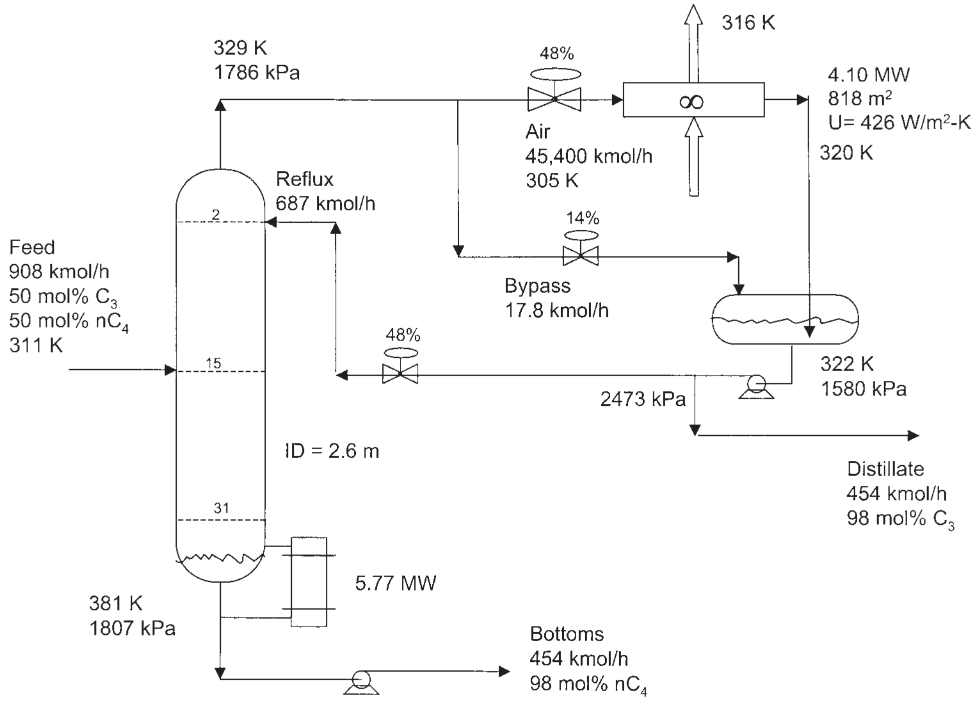

Figure 7. Control structure with hot vapor bypass.

Also observe that the design pressure drop over the vapor valve is 192 kPa with a 14 kPa pressure drop over the condenser. These design selections affect the rangeability of the system, that is, the ability of the process to handle large disturbances. The dynamic results presented below illustrate this situation. The larger the design pressure drop over the valve, the larger the disturbance that can be handled without saturating the valve. Of course the downside of higher design pressure drop is either a higher operating pressure in the column (which adversely affects energy consumption) or a lower reflux drum temperature (which increases condenser area).

Figure 9 compares the performance of this system with the

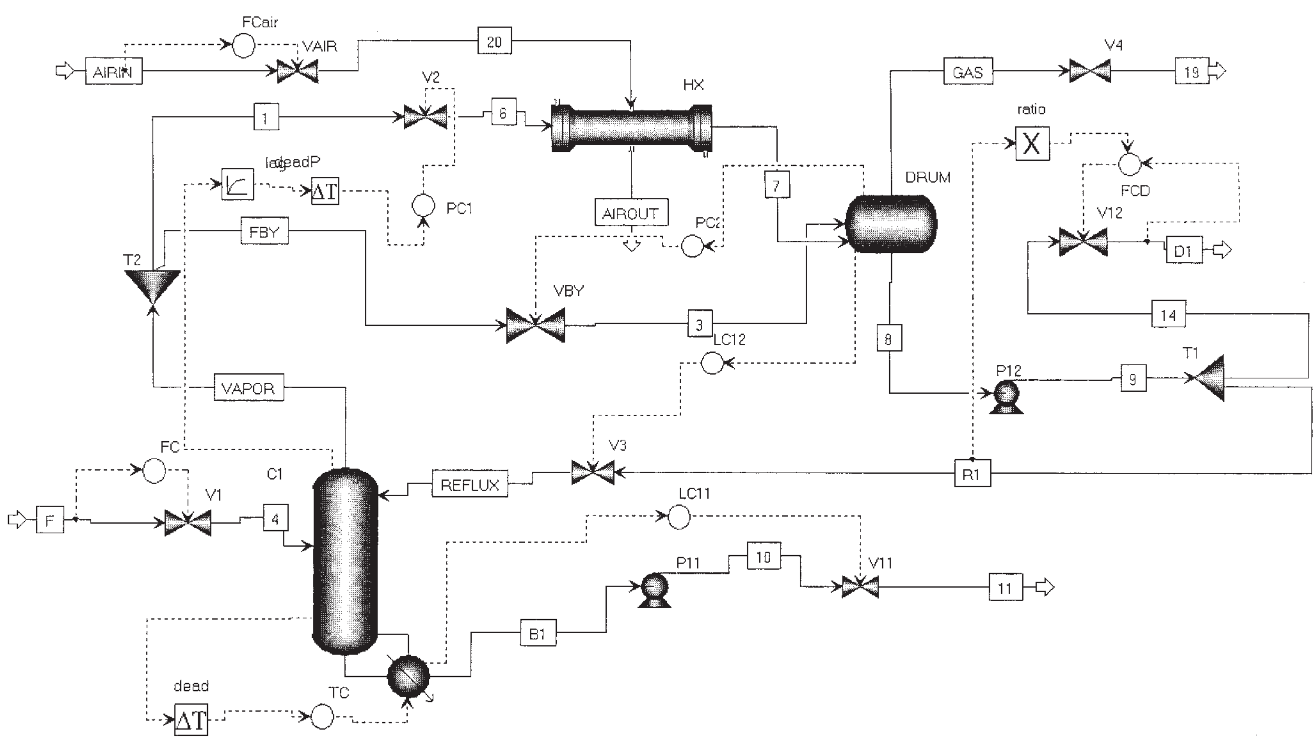

Figure 8. Flowsheet of hot vapor bypass.

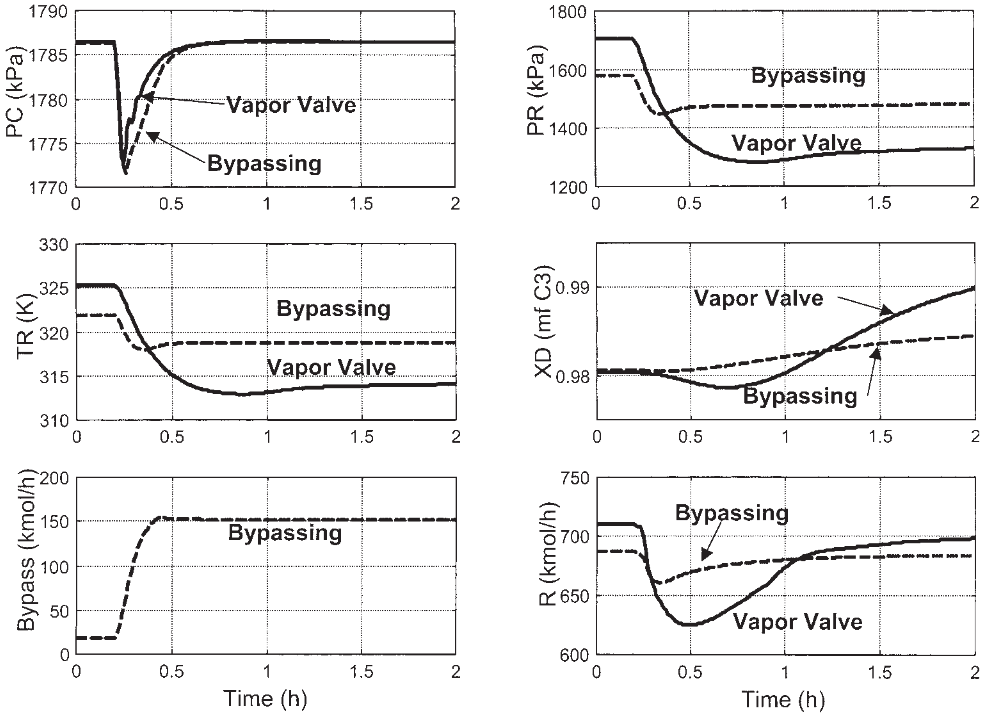

Figure 9. Comparison of vapor valve and bypass.

Air inlet 305 to 294 K.

performance of the vapor-valve system. The disturbance is a drop in air inlet temperature from 305 to 294 K. The control of column pressure is essentially the same using the bypass scheme (dashed lines) as using the vapor-valve scheme (solid lines).

The bypass valve goes wide open, with the bypass flow rate increasing from 17.8 to 150 kmol/h. Reflux-drum pressure is not held at 1589 kPa but lines out at about 1477 kPa, which is higher than the low pressure produced in the other scheme. There is less reflux subcooling, as indicated by the small change in distillate composition.

Figure 10 shows how the bypass system responds to changes in column feed flow rate. The feed flow rate is increased at time equal 0.2 h by either 10 or 20%. In both cases the bypass valve goes completely shut, and reflux-drum pressure cannot be controlled at 1580 kPa. For the 10% feed flow rate change, reflux-drum pressure levels out at 1615 kPa. Column pressure, however, is maintained at the desired 1786 kPa by opening the vapor valve further. The valve is able to compensate for the lower available pressure drop and the higher flow rate of overhead vapor.

However, for the 20% increase, reflux-drum pressure climbs to 1670 kPa. The vapor valve also goes wide open but is unable to hold column pressure at 1786 kPa, which rises to 1807 kPa. These results illustrate the need for careful design of the plumbing and hydraulics (valve sizing and design pressure drops) to address the rangeability issue.

Figure 11 gives results for changes in feed composition. Two cases are shown. In the first (solid lines), the propane composition in the feed is increased from 50 to 60 mol %. In the second (dashed lines), it is decreased to 40 mol % C_3. The decrease in propane in the feed is handled without any valve saturation because the overhead vapor flow rate decreases. However, the large increase in propane in the feed saturates both the bypass and the vapor valve. Column pressure levels out at 1834 kPa, and reflux-drum pressure levels out at 1697 kPa.

The bottoms product composition is maintained fairly close to the desired 98 mol % nC_4, but the distillate composition drops to a level of $<$94 mol % for the decrease in feed propane composition. Remember that the selected control structure holds the reflux ratio constant (RR structure). These results indicate that it might be better to select some alternative structure to improve the steady-state performance of the system in terms of product quality for feed composition changes (particularly the distillate purity).

An obvious alternative is to switch to a control structure in which reflux-drum level is controlled by manipulating the distillate flow rate and the reflux-to-feed ratio is controlled (R/F structure). Figures 12 and 13 give results using this structure. Figure 12A compares the results for the R/F structure with those of the RR structure for a change in feed composition from 50 to 60 mol % propane. In the R/F structure, the reflux flow rate does not change, so the vapor flow rate from the top of the column does not change as much. The vapor valve does not saturate, so column pressure is held at 1786 kPa. Both the distillate and the bottoms purities stay close to their desired specification for the R/F control structure. Notice that the bypass valve saturates with both structures, but the change in the reflux drum pressure is less in the R/F structure.

Figure 12B compares the results for the R/F structure with those of the RR structure for a change in feed composition from 50 to 40 mol % propane. Distillate and the bottoms purities stay close to their desired specification for the R/F control structure. Column pressure is held at 1786 kPa with

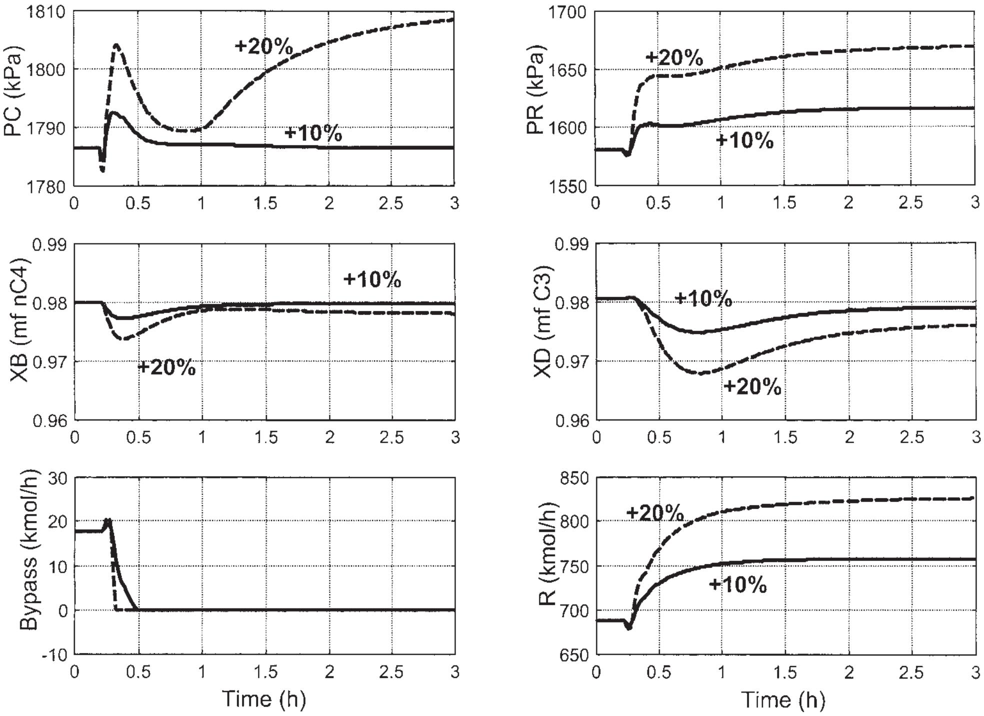

Figure 10. Bypass scheme with +10 and +20% feed rate changes.

both structures. The bypass valve does not saturate in either structures, but the change in the bypass flow rate is less in the R/F structure.

Figure 13A compares the results for the R/F structure with those of the RR structure for a +20% change in feed flow rate. The final steady-state flow rates and compositions are identical, but the dynamic responses are somewhat different. Figure 13B compares the results for the R/F structure with those of the RR structure for the inlet air temperature disturbance. The responses are quite similar except for the changes in reflux flow rate, which undergoes more of a transient in the RR structure.

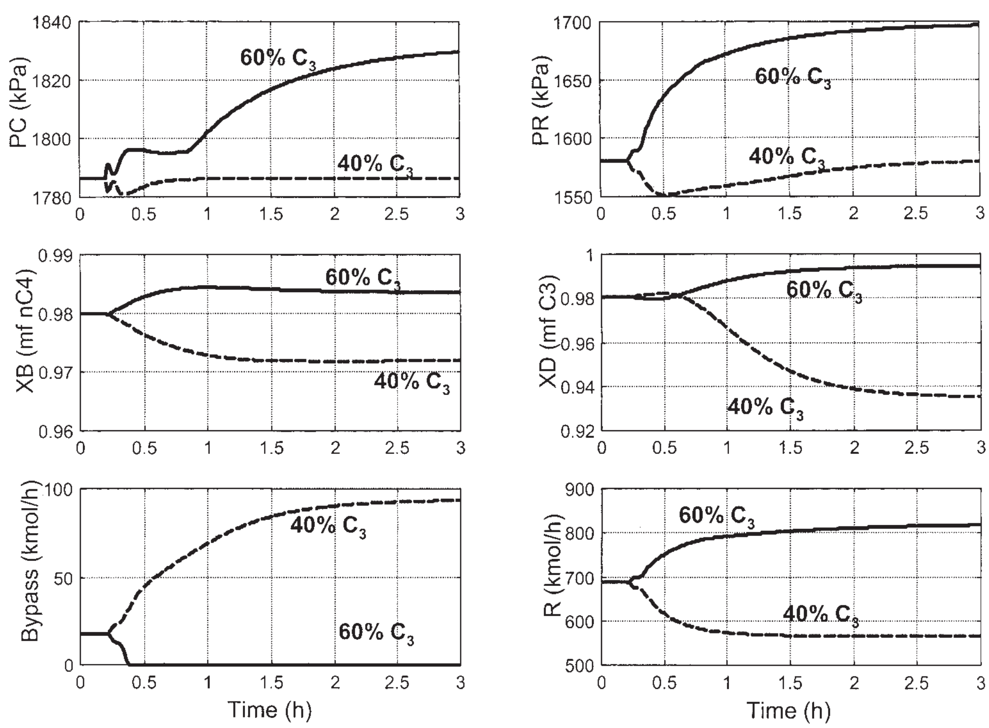

Figure 11. Bypass scheme with feed composition changes.

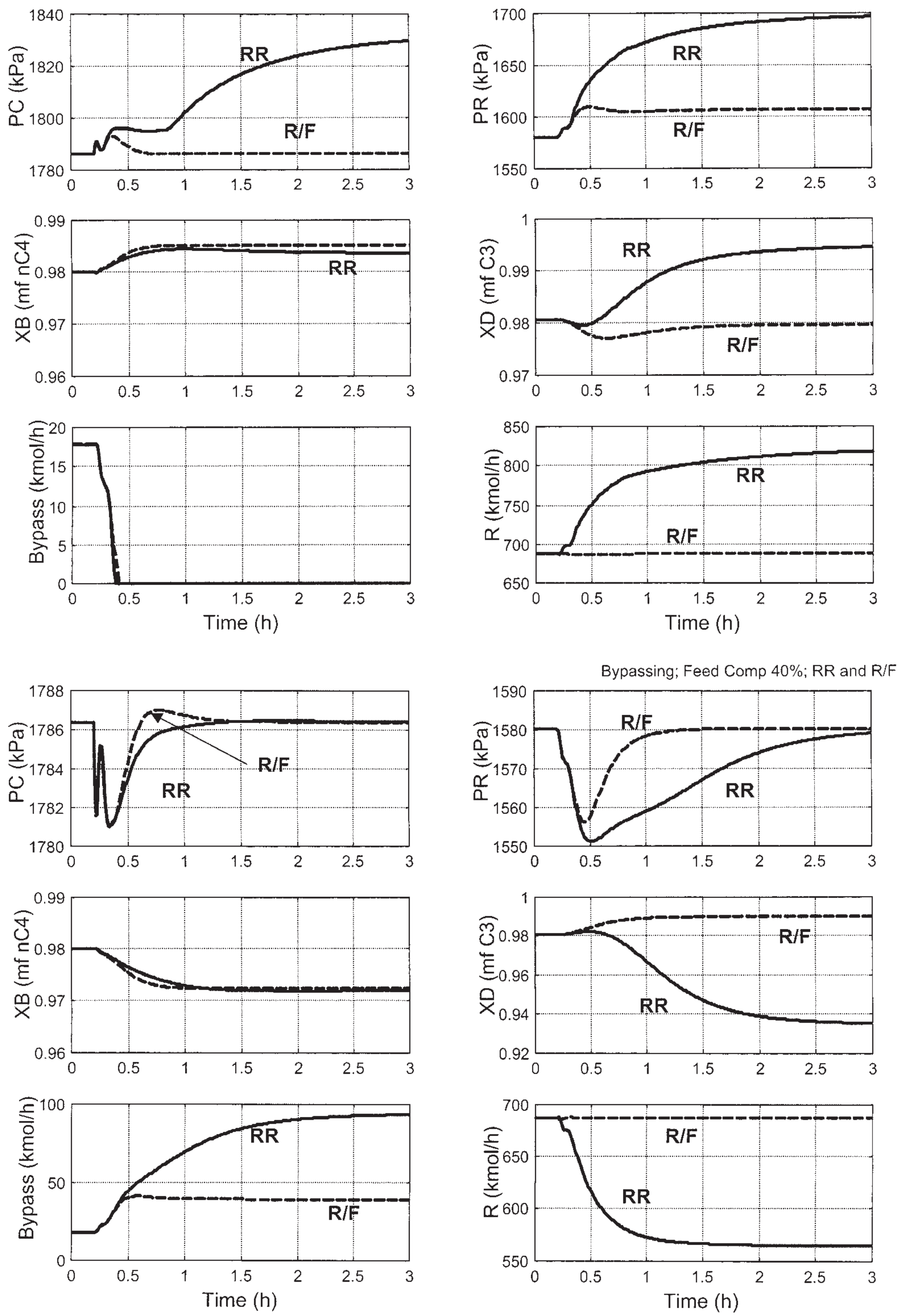

Figure 12. (A) Bypass scheme; RR and R/F with feed composition 60% C_3. (B) Bypass scheme; RR and R/F with feed composition 40% C_3.

Conclusion

This article has presented a quantitative analysis of several alternative control structures for air-cooled condensers. Manipulation of air flow rate is not only difficult from a mechanical perspective, but also produces larger changes in column pressure and slower recovery from disturbances. Control of column pressure using a valve in the overhead vapor line gives very tight column pressure control, but generates large changes in reflux-drum temperature and pressure, which influence column performance and reflux pump head requirements.

The hot-vapor bypass system gives good column pressure control and moderates the changes in reflux-drum conditions.

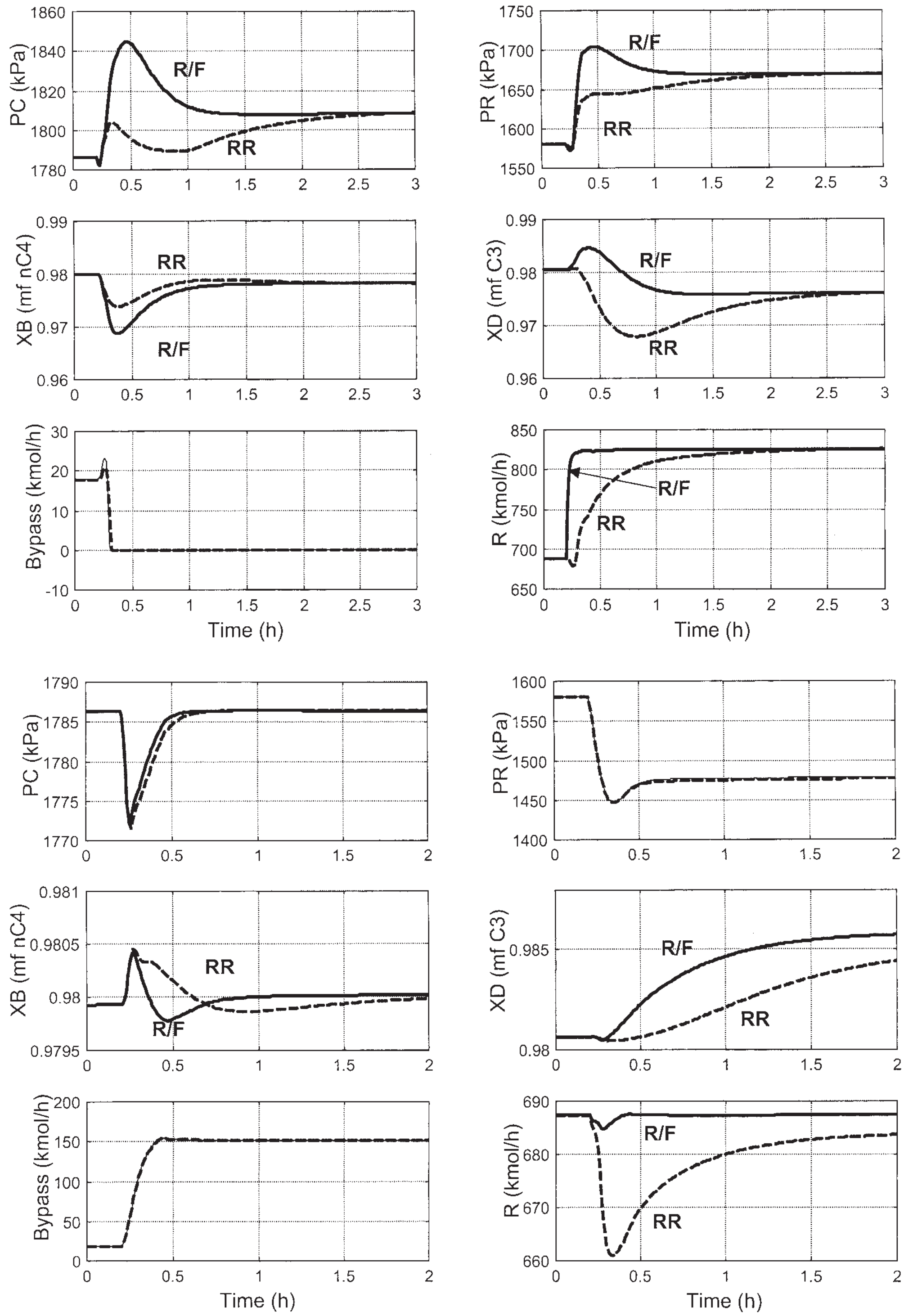

Figure 13. (A) Bypass scheme; RR and R/F with +20% feed rate; (B) bypass scheme; RR and R/F with air inlet 305 to 294 K.

However, the piping and control systems are more complex. Close attention to hydraulics is required for stable operation and to avoid valve saturation.

The disturbance that most severely influences the performance of air-cooled heat exchangers is a change in ambient conditions. The bypass system is able to effectively handle this problem.

In this article we have considered only distillation columns that have total condensers, that is, the distillate is removed as a liquid. If the distillate product is produced as a vapor and a partial condenser is used, pressure can be effectively controlled by manipulating the vapor distillate flow rate, provided this flow rate is not too small. However, manipulation of the condenser heat removal is still necessary because it is often used to control the reflux-drum level when the reflux flow rate is fixed—thus the difficult problems associated with air-cooled condensers still exist in these partial condenser systems.

Notation

D = dead time, min
K_C = controller gain (dimensionless)
PC = column pressure, kPa
PR = reflux-drum pressure, kPa
R = reflux flow rate, kmol h^{-}
TR = reflux-drum temperature K
$T25$ = Stage 25 temperature K
x_B = bottoms composition, mf *n*-butane
x_D = distillate composition, mf propane
τ = lag in pressure control loop, min
τ_I = controller integral time, min

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Manuscript received Jan. 18, 2005, and revision received Jun. 27, 2005.