

## Article

## Using hot-vapor bypass for pressure control in distillation columns



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## ABSTRACT

Distillation column control is widely explored in literature due to its complexity and importance in chemical and petrochemical industries. In this process, pressure represents one of the most important variables to be controlled. However, there are few studies about how pressure affects the dynamic behavior of distillation columns and most research on distillation column control involve direct manipulation of cooling fluid through the condenser. Nevertheless, such an approach demands constant changes in cooling fluid flowrates that are commonly by the order of tons per hour, which can be difficult to work or even unfeasible in a real plant. Furthermore, this strategy is usually avoided, as it can cause fouling and corrosion acceleration. The hot-vapor bypass strategy fits well as a solution for these issues, eliminating the need to dynamically manipulate cooling fluid flowrates in the condensation unit. This work presents the modeling and simulation of a conventional distillation column for the separation of water and ethanol, in which a comparative study between a conventional pressure control and a control using hot-vapor bypass was performed. The main results were obtained through dynamic simulations which considered various disturbances in the feed stream, and demonstrated superior performance by the hot-vapor bypass system over the usual scheme proposed in literature, while evaluating the Integral Absolute Error (IAE) norm as the control performance index.

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## 1. Introduction and Problem Definition

The study and development of efficient control structures for specific variables of a distillation system, meaning mainly a column's top pressure and temperature, are of extreme importance to reduce the effect of potential disturbances which may occur during the operation of any distillation column, whether coming from changes in nominal conditions or failures in upstream or downstream processes that are directly or indirectly connected to the main separation unit.

Fluctuations in a column's top pressure and feed conditions around their operational values have a strong relation to undesired changes in temperature and composition profiles throughout the column, as well as with separation efficiency, since these factors are related to relative volatility between components in each stage. Thus, variations in these variables will induce vaporization of heavy components and condensation of light components, thereby obtaining a non-conforming final product and ultimately affecting process economy.

Pressure is the most important variable to control in distillation columns, because it affects condensation, vaporization temperatures, volatilities and almost all the processes that occur in the column [1]. However, the assumption of constant pressure is often justified because

pressure is tightly controlled, but overall pressure dynamics and their effect on the column behavior are not well understood [2].

In fact, there are few studies about how pressure affects the dynamic behavior of distillation columns and their control system. An efficient control of a column's top pressure in a distillation unit can minimize potential compensations in temperature throughout its operations due to disturbances or relevant noise, as well as preventing flooding within the column [3]. A fair number of configurations for pressure control in vacuum and low/average-pressure distillation columns were studied, pointing out their main characteristics and requirements for a successful application; however, only a qualitative discussion is presented. The importance of pressure control on dividing wall columns (DWCs) to keep the vapor flowrate on either side of the wall as designed was also studied, but no numerical study is presented [4].

There are several ways to control column pressure, depending on how the column is configured, but the most common pressure control strategy in a distillation column involves the manipulation of cooling fluid flowrate. However, since water is the main cooling fluid used, this strategy is usually avoided, as it can accelerate fouling and corrosion in condensers [1].

Although manipulation of cooling fluid flowrate strategy works well in a simulation environment for pressure control [5–14], it is a difficult solution for the pressure control problem in most real distillation systems, because the flowrate of cooling fluid is an input variable which must be manipulated at high flowrates, which can be difficult

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or even unfeasible in real plants, as it is hard to manipulate a necessarily large valve for such a huge demand of cooling fluid.

A commonly used alternative to avoid manipulation of cooling fluid flowrate is to partially flood the condenser with process liquid by placing a control valve after the condenser; changes in the liquid level change the heat-transfer area, which changes the condenser duty; the cooling fluid flowrate is fixed [15]. On the other hand, another study does not recommend the use of a flooded condenser operation with a valve after the condenser, because the heat-transfer area is a non-linear function of the amount of process liquid in the condenser [16].

The use of hot-vapor bypass system for pressure control of distillation columns does not require the direct manipulation of the cooling fluid flowrate; it assumes the split of a hot stream such that a portion of this stream is redirected to promote fast dynamics in a specific part of the process, thus offering a fair condition for the control of a desired variable.

An adequate usage of the hot-vapor bypass strategy for air-cooled condensers is a satisfactory alternative for the column pressure problem among other explored approaches, such as direct modulation of the overhead stream valve and cooling fluid manipulation in the condenser, since the latter have considerable implementation and maintenance issues [17].

The implementation of control schemes which include hot-vapor bypass for heating and cooling of liquid streams through heat exchangers was investigated [18]; according to the results, the addition of a hot-vapor bypass stream around the heat exchanger can promote robust control of the outlet temperature by manipulating the bypass flowrate, providing a product stream in a suitable temperature for a specific downstream process. In a distillation unit using hot-vapor bypass, the hot stream is the overhead vapor coming from the top of the column, with a portion of it being redirected to the reflux drum, as demonstrated in Fig. 1.

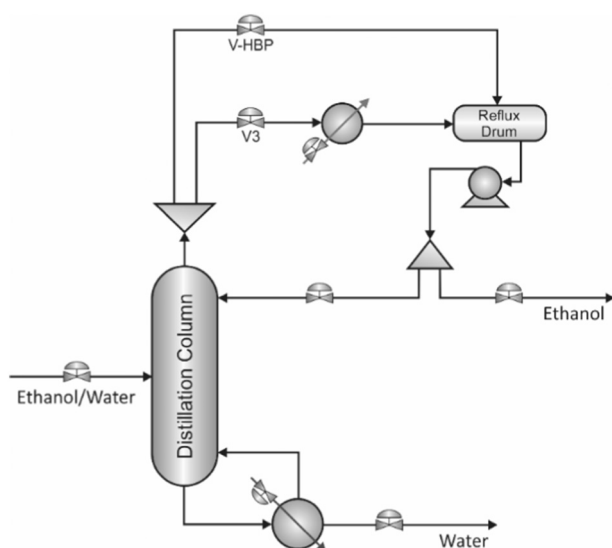


Fig. 1. Flowsheet (PFD) for a conventional distillation system with hot-vapor bypass.

According to Fig. 1, the dynamics of top column pressure are affected by the manipulation of hot-vapor bypass stream valve (V-HVBP) or vapor stream valve (V3), thus making it possible to control pressure in such a manner that when the column pressure rises, the pressure controller manipulates the valve(s) to reduce vapor pressure within the column.

The present investigation discusses alternative control systems for pressure control in a distillation column through the adequate inclusion of a hot-vapor bypass stream connecting the column and reflux drum, keeping both the heat-transfer area of the condenser and the cooling

fluid flowrate constant. Through dynamic simulations, it was observed that column and reflux drum pressure control were successfully achieved, while also evaluating the Integral Absolute Error (IAE) norm as the control performance index when considering various disturbances in the column's feed stream. This is a decent contribution to the field since there is a lack of scientific investigation exploring the simulation of hot-vapor bypass as a practical and consistent option for performing pressure control in reality.

## 2. Process Studied and Control Configurations

The PFD presented in Fig. 1 was implemented with Aspen Plus® (steady-state) using the *RadFrac* routine. The simulated column has a total of 29 stages (counted from top to bottom), including the reboiler, while the condenser and reflux drum were decoupled from the columns to obtain a more rigorous and realistic model. The condenser and reflux drum were simulated with *Heater* and *Flash2* routines, respectively; moreover, total condensation was assumed, leading to no vapor production in the reflux drum. Phase equilibrium (VLE) was represented through a  $\gamma - \phi$  approach with NRTL model for activity coefficient calculations ( $\gamma$ ). The vapor phase was considered ideal ( $\phi = 1$ ) due to low system pressure.

The diameters of the column were calculated using the Column Internal/Interactive Sizing mode from Aspen Plus®, while the length and diameter of the reflux drum and sump height were calculated for a 5-minute hold-up [19]; the column diameter was 1.84 m, sump height was 1.78 m and the reflux drum volume was 6.1 m<sup>3</sup>.

In order to reach the top and bottom specifications, reflux and boil-up ratios were set as equal to 4.01 and 1.47, respectively, which corresponds to a reboiler heat duty equal to 8059.7 kW and a condenser heat duty of 7149.9 kW. The data for the global distillation column streams are shown in Table 1.

Table 1  
Data for global streams

| Variable                              | Feed          | Distillate | Bottom |
|---------------------------------------|---------------|------------|--------|
| Temperature/K                         | 308.1         | 351.4      | 373.1  |
| Pressure/ $\times 10^{-5}$ /Pa        | 1.50          | 1.0132     | 1.2184 |
| Flowrate/kmol $\cdot$ h <sup>-1</sup> | 600           | 130.12     | 469.88 |
| Component                             | Mole fraction |            |        |
| Water                                 | 0.80          | 0.1500     | 0.9800 |
| Ethanol                               | 0.20          | 0.8500     | 0.0200 |

Once the steady-state model converges numerically and no physical inconsistencies are found, it is then exported to the dynamic platform Aspen Plus Dynamics®, where the control loops are implemented and properly tested. Fig. 2 presents the control structure with manipulation of cooling fluid flowrate, called the base-case, established as the following:

- (1) Sump liquid level is controlled by manipulating bottom flow rate;
- (2) Reflux drum liquid level is controlled by distillate flow rate manipulation;
- (3) The ratio between feed and reflux flowrates was kept constant;
- (4) Temperature control is performed through manipulation of steam flow rate in the reboiler;
- (5) Top pressure is controlled by manipulating cooling fluid flowrate;
- (6) A flowrate controller was added in the feed stream to introduce disturbances.

The slope criteria was applied to determine the best stage to have its temperature controlled, which consists in selecting the tray where

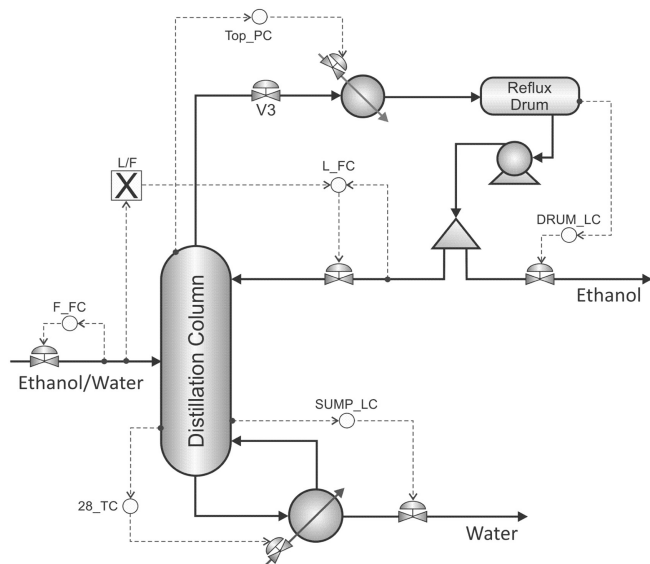


**Fig. 2.** Control structure manipulating the cooling fluid flowrate to pressure control (base-case).

considerable temperature variations exist from tray to tray; the column temperature of stage 28 is recommended to be controlled.

Only level controllers are proportional (P), while pressure, flowrate and temperature controllers are proportional-integral (PI). A dead time block of 2 min was added before the temperature controller. The controllers were tuned [20], and the obtained results (the same values for all cases) are summarized in Table 2.

**Table 2**  
Controller parameters

| Controller | Controlled variable           | Manipulated variable                        | $K_c$ | $\tau_i$ /min |
|------------|-------------------------------|---------------------------------------------|-------|---------------|
| L_FC       | Reflux to feed flowrate ratio | Reflux rate                                 | 0.5   | 0.3           |
| 28_TC      | Temperature stage 28          | Heating fluid                               | 1.9   | 13.2          |
| Sump_LC    | Sump level                    | Bottom flowrate                             | 10    | –             |
| Drum_LC    | Reflux drum level             | Distillate flowrate                         | 10    | –             |
| Drum_PC    | Reflux drum pressure          | Cooling fluid or overhead vapor flowrate    | 20    | 10            |
| Top_PC     | Top pressure                  | Overhead vapor or hot-vapor bypass flowrate | 20    | 10            |

For an approach (difference between fluid process inlet temperature and cooling fluid outlet temperature) of 15 K, the UA product (overall heat transfer coefficient  $\times$  heat-transfer area) is 168.9 kW·K<sup>-1</sup>. Condenser heat duty is removed by 408566 kg·h<sup>-1</sup> of incoming cooling water at 301 K. The investigation of the hot-vapor bypass strategy for the column's pressure control was performed considering three distinct configurations of manipulated variables:

- Configuration I: manipulation of overhead vapor flowrate to the condenser;
- Configuration II: manipulation of overhead vapor flowrate to the hot-vapor bypass stream;
- Configuration III: simultaneous manipulation of overhead vapor flowrates to the condenser and to the hot-vapor bypass stream.

Control configuration I aims to keep the pressure constant at the top of the column through manipulation of overhead vapor coming from the column and entering the condenser unit, as shown in Fig. 3. Such manipulation is performed by modulating the condenser stream valve's degree of opening, while the hot-vapor bypass valve is unaltered.

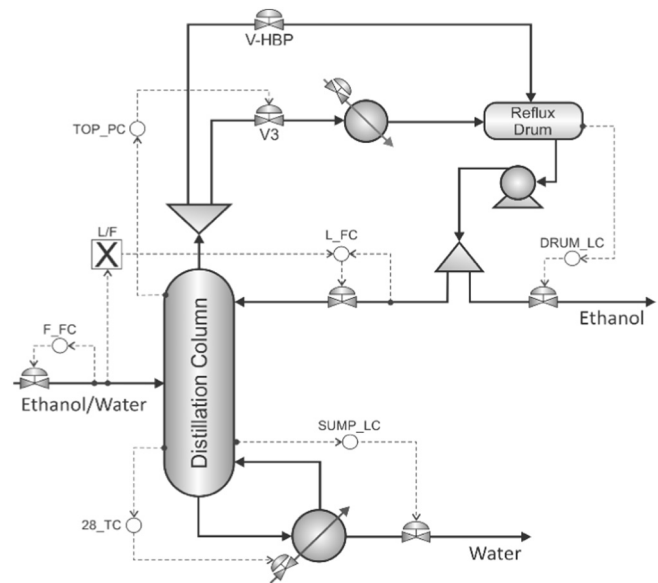


**Fig. 3.** Control structure manipulating the vapor flowrate to condenser (configuration I).

Furthermore, the following procedures are recommended to obtain a stable column top pressure upon simulating disturbances in the feed stream:

- Deploy the regulatory control;
- Deploy the ratio control between feed and reflux flowrates;
- Fix reflux drum and column sump liquid level at 50%;
- Run the simulation until the level reaches the set point;
- Deploy temperature controller and perform tuning actions;
- Deploy pressure controller and perform tuning actions.

In control configuration II (as depicted in Fig. 4), the pressure on the top stage of the column is kept constant through manipulation of overhead vapor coming from the column and is redirected into the reflux drum through the bypass stream; manipulation of bypass vapor flowrate is executed by modulating the bypass stream valve's degree of opening, while condenser stream valve remains unchanged.

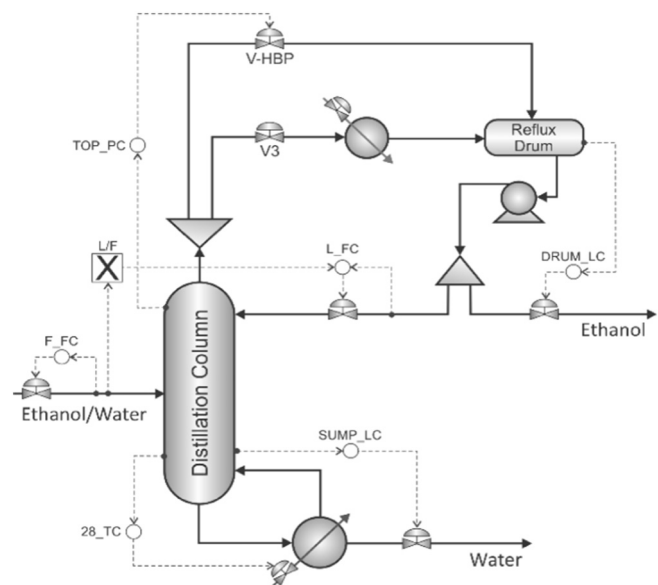


**Fig. 4.** Control structure manipulating the vapor flowrate to hot-vapor bypass (configuration II).

The same procedures for configuration I are recommended for a stable simulation with configuration II.

Control configuration III was designed to perform pressure control in both the top of the column and the reflux drum using the condenser stream and bypass stream valves simultaneously, thus consisting of a multivariable  $2 \times 2$  control system. Fig. 5 shows the control scheme of configuration III. The same procedures for configuration I are recommended for a stable simulation of the hot-vapor bypass strategy following this configuration.

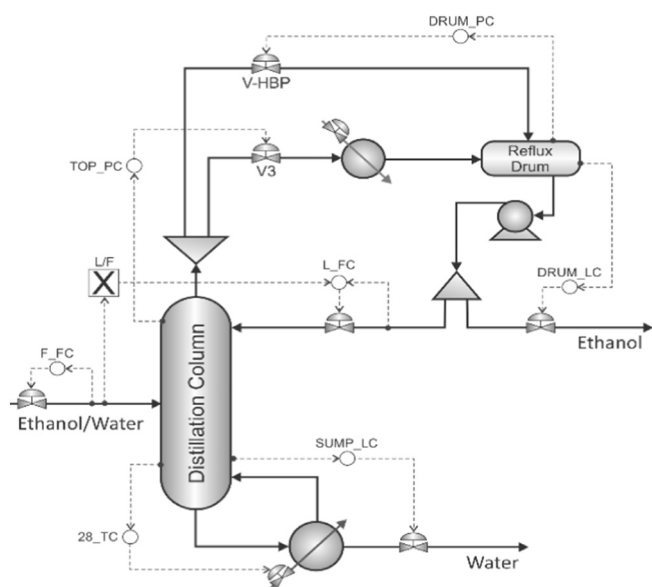


Fig. 5. Control structure with dual pressure control (configuration III).

The use of hot-vapor bypass for pressure control requires subcooled liquid from the condenser to avoid vent from the reflux drum to atmosphere or increasing the drum pressure; this results in condensers with larger heat-transfer areas. Fig. 6 shows the heat-transfer area and split fraction redirected to hot-vapor bypass as a function of subcooling degree.

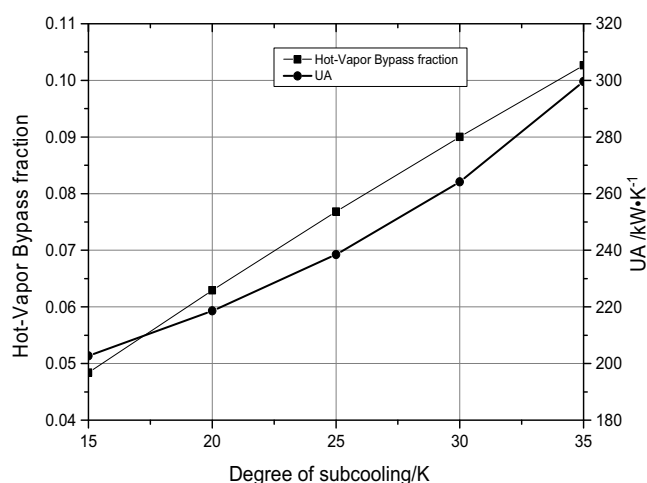


Fig. 6. Split fraction redirected to hot-vapor bypass and heat-transfer area as a function of the subcooling degree.

### 3. Dynamic Results

Before presenting the results for the three proposed control configurations, Figs. 7–9 show the dynamic behavior of top pressure and

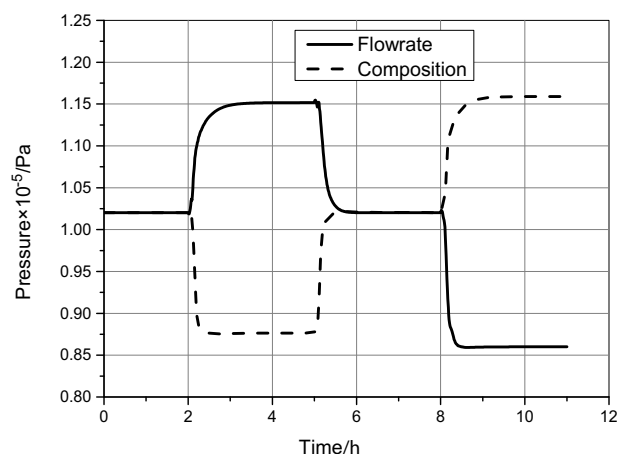


Fig. 7. Open loop top pressure responses for feed disturbance in the base case.

composition (ethanol) at the top and bottom of the column, respectively, for  $\pm 10\%$  disturbances in the feed stream, with open loop top pressure for the base case:

- The flowrate was increased to  $660 \text{ kmol} \cdot \text{h}^{-1}$  at time equal to 2 h, and it was reduced to  $540 \text{ kmol} \cdot \text{h}^{-1}$  at 8 h;
- The composition (water) was increased to 88 mol% at time equal to 2 h and it was reduced to 72 mol% at 8 h.

Due to the small change (from 87500Pa to  $1.15 \times 10^5 \text{ Pa}$ ) as depicted in Fig. 7, the effect of pressure on the K-values can be neglected. However, even this small change in pressure (not only in the top, but throughout the column) is sufficient to cause large deviations in the distillate (Fig. 8a), and mainly in the bottom (Fig. 8b) compositions. These deviations are due to modifications in mass and energy balances after changes in feed conditions (flowrate or composition), in addition to the action of temperature, level and ratio controllers.

For positive disturbance, the mass flowrate inside the column increases, and the reboiler heat duty increases to reach the temperature set-point; as a result, the vapor flowrate at the top of the column also increases. As the cooling water flowrate is kept constant (controller in manual mode), the temperature (dew point) in the condenser outlet stream increases by  $3^\circ \text{C}$ ; then the stream has two phases into the reflux drum for some minutes, however, the vapor phase disappears when pressure increases. In summary, pressure behavior throughout the column strongly depends on the withdrawal of energy by the condenser.

The UA product value chosen for hot-vapor bypass configurations is  $264.2 \text{ kW} \cdot \text{K}^{-1}$  (30 K of subcooling); this value is 56.5% greater than the base case, for a split fraction close to 9%. Condenser heat duty is the same as the base case. The UA value was chosen by comparing all hot-vapor bypass configurations using the same condenser heat transfer area. Table 3 depicts the results for stable top pressure control as a function of the subcooling degree for  $\pm 10\%$  disturbances in feed flowrate and composition.

According to Table 3, it is possible to use a hot-vapor bypass configuration (II and III) with 15 K degrees of subcooling, which would result in a lower heat transfer area ( $UA = 202.7 \text{ kW} \cdot \text{K}^{-1}$ ) and is 20% greater than the base case.

Fig. 9 presents the top pressure dynamic responses (closed-loop) for the three proposed configurations. According to the results, all hot-vapor bypass configurations could keep the top pressure in its set-point. Compared to the base case, hot-vapor bypass configurations present superior control performance, i.e. lower overshoots.

Due to the elevated number of results for top and bottom ethanol compositions, the comparison between hot-vapor bypass and base

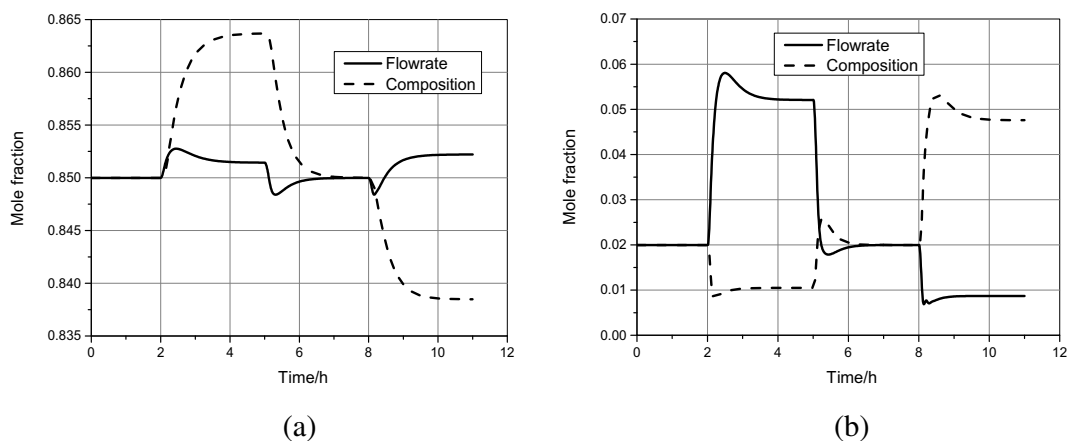


Fig. 8. Dynamic responses of ethanol mole fraction at distillate (a) and bottom (b). Open-loop top pressure for base case.

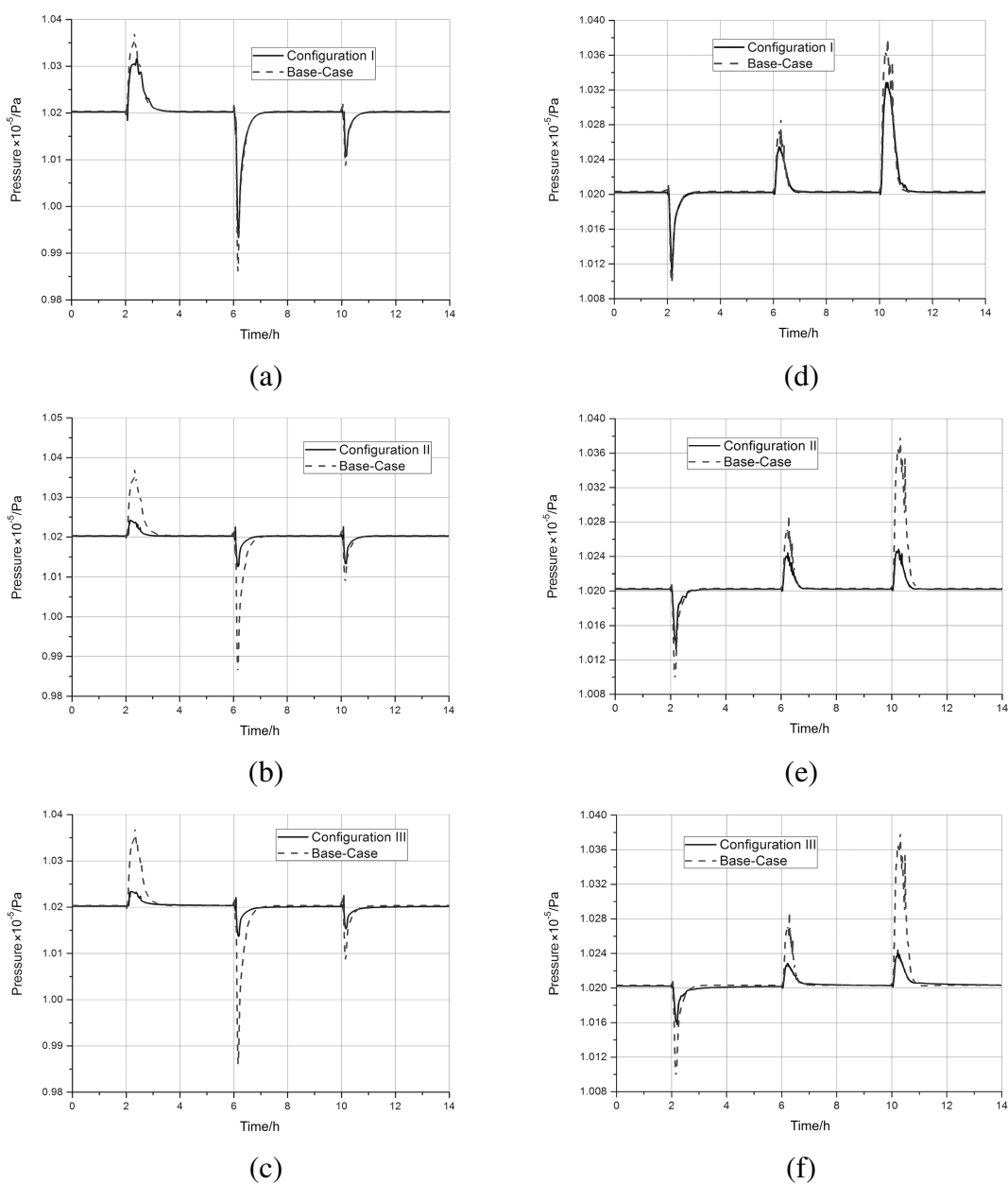


Fig. 9. Dynamic responses of top pressure for feed flowrate (a, b and c) and feed composition (d, e and f) disturbances.

**Table 3**

Stable pressure control as a function of subcooling degree in the condenser

| Subcooling degree /K | Configuration I |   |             |   | Configuration II |   |             |   | Configuration III |   |             |   |
|----------------------|-----------------|---|-------------|---|------------------|---|-------------|---|-------------------|---|-------------|---|
|                      | Flowrate        |   | Composition |   | Flowrate         |   | Composition |   | Flowrate          |   | Composition |   |
|                      | +               | – | +           | – | +                | – | +           | – | +                 | – | +           | – |
| 15                   | n               | y | y           | n | y                | y | y           | y | y                 | y | y           | y |
| 20                   | n               | y | y           | n | y                | y | y           | y | y                 | y | y           | y |
| 25                   | n               | y | y           | n | y                | y | y           | y | y                 | y | y           | y |
| 30                   | y               | y | y           | y | y                | y | y           | y | y                 | y | y           | y |
| 35                   | y               | y | y           | y | y                | y | y           | y | y                 | y | y           | y |

y: top pressure was controlled.

n: top pressure was not controlled.

case will only be presented for configuration I, which presented lower performance. As depicted in Figs. 10 and 11, the performance for configuration I and the base case are identical; the lower overshoot of configuration I does not affect top or bottom compositions.

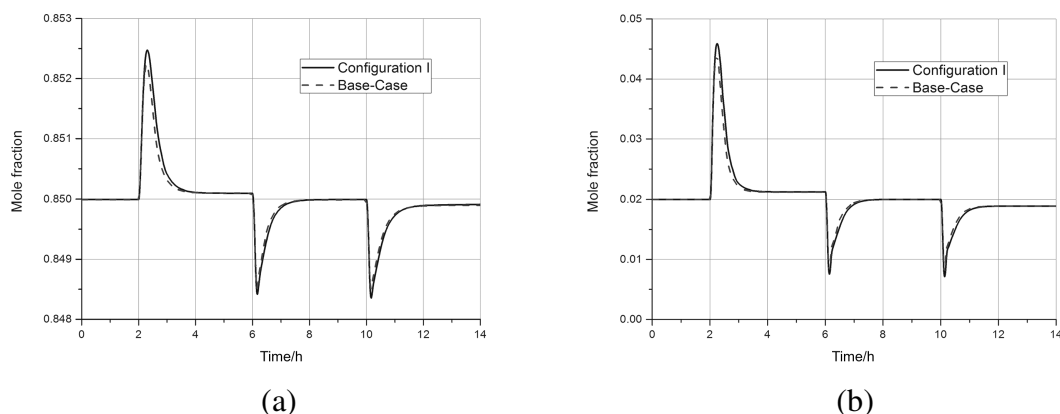
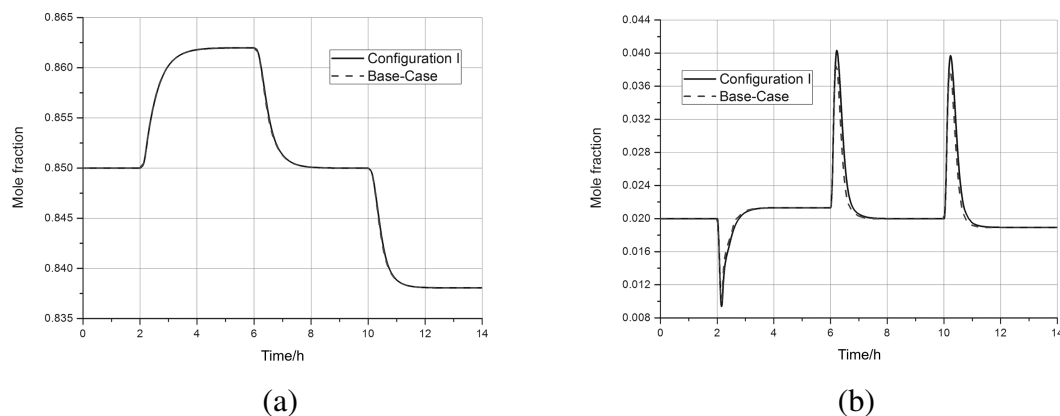
For hot-vapor bypass configurations, the cooling fluid flowrate is kept constant; therefore, only two curves will be presented in comparing the base case's dynamic behavior of this variable.

Fig. 12 presents the dynamic behavior of the cooling fluid flowrate, and as can be observed after the positive disturbance in the feed flowrate (Fig. 12a), the flowrate increases from 408 to 926  $\text{t} \cdot \text{h}^{-1}$  to keep the top pressure at its set-point. This would require a fairly large valve, which in practical terms might be infeasible or would demand high maintenance values. For negative disturbance (Fig. 12b), the cooling fluid flowrate changes from 408 to 249  $\text{t} \cdot \text{h}^{-1}$ , which is

another large modification. An identical behavior for the cooling flow rate is observed for disturbance in the feed composition. In some plants, throttling the cooling water flow rate is undesirable because fouling problems arising from low velocity can allow solids to deposit in the cooling water [17].

From a process point of view, the dynamic behavior of the cooling flow rate is proportional to the vapor flowrate from the top of the column. Since a large change is observed, it is very common to operate the condensers in an industrial plant with the cooling fluid flowrate valve completely open (100%); but this can result in high energy consumption.

Another important variable is the outlet temperature of cooling fluid. Fig. 13 presents the results for the base case and all configurations using hot-vapor bypass. As can be observed, the outlet temperature

**Fig. 10.** Dynamic responses of ethanol mole fraction in the distillate (a) and bottom (b) for feed flowrate disturbance.**Fig. 11.** Dynamic responses of ethanol mole fraction in the distillate (a) and bottom (b) for feed composition disturbance.

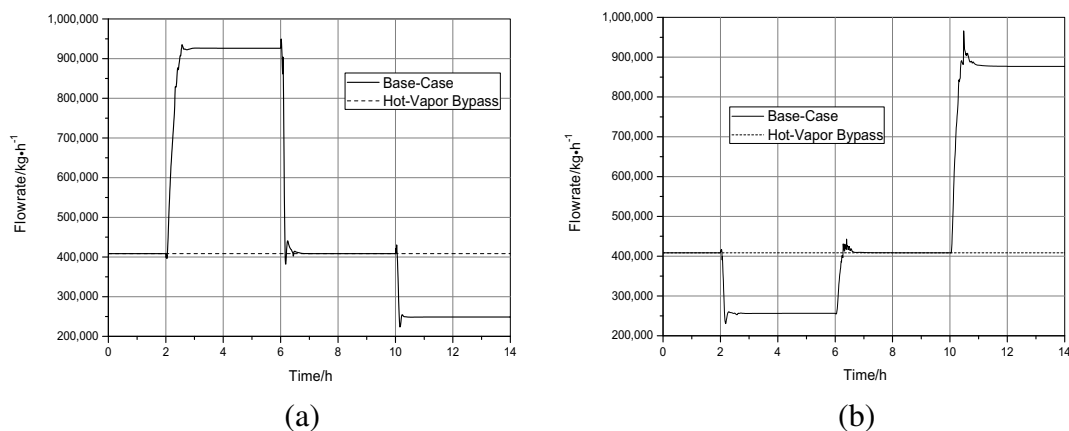


Fig. 12. Dynamic responses of the cooling fluid flowrate for feed flowrate (a) and feed composition (b) disturbances.

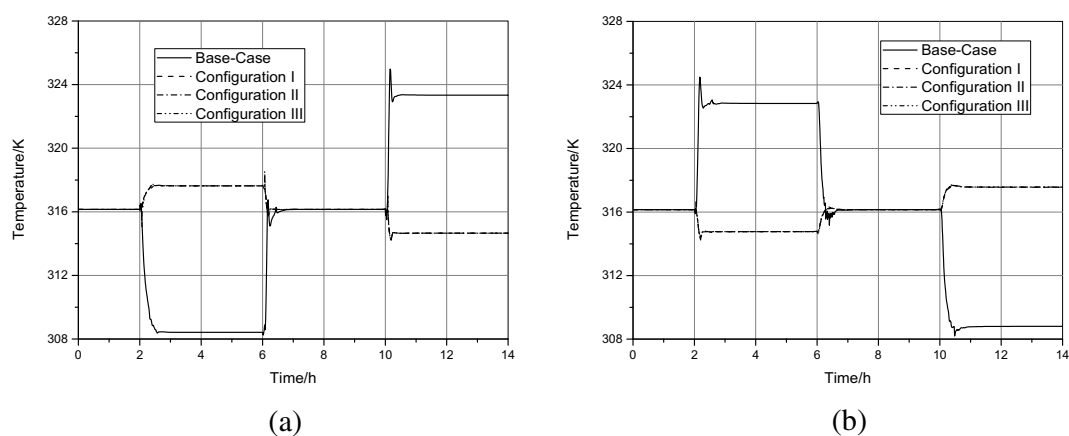


Fig. 13. Dynamic responses of cooling fluid outlet temperature for feed flowrate (a) and feed composition (b) disturbances.

for the base case reaches values superior to 323 K; this does not occur with the hot-vapor bypass configurations. It is important emphasize that high temperatures increase the corrosion in the condenser [17]. In addition, the cooling fluid returning to the cooling tower at a high temperature may result in some problems such as a high evaporation rate.

It is important to emphasize that it is possible to use a smaller cooling fluid flowrate for the base case than what is presented in Fig. 12, but one of two options should be chosen for the condenser:

increase the temperature approach or the heat-transfer area. However, the bigger impact is caused by the temperature approach and as previously mentioned, the cooling fluid outlet temperature value is already very high.

Another important aspect of a control strategy is the behavior of the manipulated variable (MV), which is normally a valve. Fig. 14 presents the dynamic behavior of the MV for disturbances in the feed flowrate (14a) and feed composition (14b) for configuration II, where it can be noted that the change in the valve opening is less than 10% for both

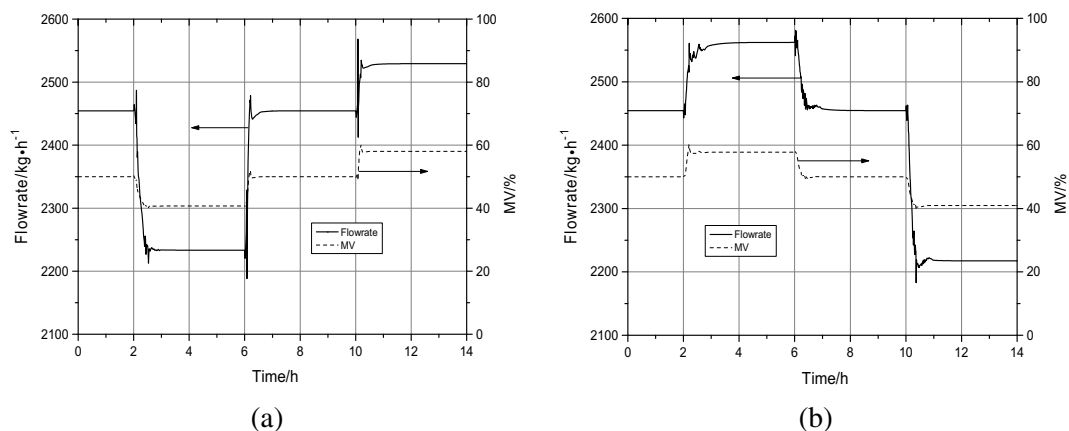


Fig. 14. Dynamic responses of cooling fluid flowrate and manipulated variable for feed flowrate (a) and feed composition (b) disturbances: configuration II.

disturbances. Furthermore, the change in the hot-vapor bypass flowrate is also close to 10% for both disturbances. From an industrial point of view this means using small valves.

#### 4. Control Performance Analysis

Considering all the results obtained by hot-vapor bypass configurations and due to its operational and implementation simplicity, the best choice would be configuration I or II; i.e. only manipulating one valve, because configuration III assumes a higher complexity compared to the others as it undergoes a multivariable  $2 \times 2$  system in which (inherent to this sort of control problem) there are interactions between each control loop. However, also considering the economical point of view, the best configuration is II because of the lower heat transfer area.

Control performance indexes are commonly encountered as integral functions and basically evaluate the numerical discrepancy between a measured variable and its set-point within a time length; several indexes may be considered upon analyzing the performance of a control system, such as the integral of absolute error (IAE), integral of time multiplied by absolute error (ITAE), integral of squared error (ISE), and integral of time multiplied by squared error (ITSE) [21]. In order to evaluate disturbance rejection for the three control schemes proposed in this work, the IAE index was chosen as the quantifier for control performance in each performed simulation, because it relates to process variance and how close the set-point can be to controlled variable specification, thus being mathematically defined by Eq. (1):

$$IAE = \int_{t_0}^t |y - y^{sp}| dt \quad (1)$$

In Eq. (1)  $y$  is the controlled variable value and  $y^{sp}$  is the set-point value;  $t_0$  and  $t$  are the initial and final time. Table 4 provides numerical values for the IAE index obtained in each simulation for all configurations, relating each configuration to their disturbance variables through the IAE.

**Table 4**

IAE ( $\times 10^2$ Pa) index for performance test with each hot-vapor bypass pressure control configuration

| Disturbance | Base-case | Configuration I | Configuration II | Configuration III |
|-------------|-----------|-----------------|------------------|-------------------|
| Flow        | 16.91     | 14.27           | 4.65             | 5.92              |
| Composition | 10.96     | 9.63            | 4.22             | 4.82              |

According to Table 4, the smallest value in magnitude for the IAE average is related to configuration II, or the “pure hot-vapor bypass control configuration”. Configuration III (dual pressure control) demonstrated a better performance when compared to configuration I, indicating that the adoption of hot-vapor bypass valve modulation as the manipulated variable affected the closed-loop response form of top pressure, since configuration I demonstrated dynamic response with considerable overshoots and undershoots. In summary, configurations that assume the hot-vapor bypass valve as a manipulated variable made the top column pressure response a smoother form. This outcome is rather interesting and supports the use of the hot-vapor bypass to change the dynamics of the reflux section in a distillation column, showing the potential of its use to simplify the form of a closed-loop response, and thus turn the system into an easier one to control or manipulate set points.

#### 5. Concluding Remarks

The present work contributes to the development of alternative options to accomplish pressure control in a realistic and practical

fashion considering the problems of a distillation process, and provides explanations for the implications of inserting a hot-vapor bypass stream for pressure control.

In general, all three hot-vapor bypass control configurations investigated in this work showed decent and relevant results as alternatives for distillation pressure control against the usual strategy (base case), which involves the dynamic manipulation of the cooling fluid flowrate by  $t \cdot h^{-1}$ . However, configurations II and III assume the hot-vapor bypass valve as a manipulated variable, and have made the dynamic response of pressure softer. Furthermore, configurations II and III work with a smaller heat-transfer area.

Between II and III, modulating the hot-vapor bypass valve only in configuration II provided the most satisfactory control performance considering deviation of the top column pressure to its set point, besides configuration III assumes a higher complexity as it undergoes a multi-variable system in which there are interactions between each control loop.

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