Influence of the Location of the Internal Temperature Control Loop on the Performance of the Dual Temperature Control for Feed Temperature Disturbance

C. Marangoni,[a,*] E. J. Zierhut,[b] I. G. B. Parisotto,[c] R. A. F. Machado,[d] and A. Bolzan[e]

[a]Federal University of Santa Catarina – Blumenau Campus, Rua
Pomerode 710, Blumenau/SC, Zip Code 89065-300, Brazil

[b]University of Joinville Region, Chemical Engineering Department,
Mail Box 246, Joinville/SC, Zip Code 89219-905, Brazil

[c]Federal University of Santa Catarina – Chemical Engineering
Department, Mail Box 476, Florianópolis/SC, Zip Code 88040-900, Brazil

[d]Federal University of Santa Catarina – Chemical Engineering
Department, Mail Box 476, Florianópolis/SC,
Zip Code 88040-900, Brazil

[e]Federal University of Santa Catarina – Chemical Engineering
Department, Mail Box 476, Florianópolis/SC,
Zip Code 88040-900, Brazil

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A control strategy with distributed corrective action for distillation has been proposed and consists of a conventional dual temperature control combined with an additional column tray. In this work, we evaluated the influence of the location of this internal loop as part of the new proposal, compared to a conventional system. Tests were carried out in a 13-column tray distillation equipment and feed temperature was disturbed. Two different column trays from the stripping section were used (11 and 12) for internal decentralized temperature control, each one separately, plus the dual control of top and bottom temperatures. The results demonstrated that this proposed control approach with distributed corrective action is faster than the conventional one, regardless of the column tray in use. It was also determined that the internal loop close to the feed (disturbance) is more interesting as a way to minimize transients.

Key words:
distillation, dynamics, distributed, dual control

Introduction

The economic principles that determine the value of products and raw materials from chemical industries are supply, demand, and competition. For this reason, studies are needed in terms of optimization of parameters, systems, or processes, as their operational conditions once they will influence the overall efficiency of the plant and, therefore, process economics[1]. Almost all chemical and petrochemical industries require the separation of a solid, liquid, or gas phase into its components and, in this sense, the most widely used process is distillation. Proper process operation is essential to ensure the quality of the resulting products. Therefore, many control systems are applied.

In a distillation column, an operating time outside of the quality specified is formed when the process is disturbed, and its characteristics limit the efficiency of the control system or when the setpoint is modified. In the first case, there are aspects such as coupling, nonlinearities, high delay, and constant time and process constraints, especially in the operational column trays. In the second case, there are aspects like the system needs to be distilled; changes in feed composition, and operational transitions that are required and attributed to changes in the market requiring adjustment in a new operating point[2]. Intrinsic characteristics of the process promote high transition periods when the process is disturbed and, even with all the technology involved and complex or well-adjusted control systems, such transients can still be seen. In all cases, the process dynamics influences the way in which the transient is generated and how the final result will be achieved.

When the goal is the dual control of composition, the adjustment of the control system is further

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[*] Corresponding author: cintia.marangoni@ufsc.br (+55 48 3721-3375)

complicated by interactions between the variables at both the bottom and the top of the column. Although this control system has been extensively studied in recent decades, some new proposals have also been presented for evaluating pairing variables. Fernandez de Canete *et al.*[3] proposed the use of adaptive neural networks for the prediction of a product composition, starting from secondary variable measurements, and progressing to both dual composition and inventory control for continuous distillation. Jana *et al.*[4] studied the synthesis of nonlinear observer-based Globally Linearizing Control (GLC) algorithms for a multivariable distillation column and the Adaptive State Observer (ASO). They compared the control performance of GLC-ASO and a dual-loop proportional integral derivative (PID) controller, the first of which provided a better closed-loop response. Enagandula and Riggs[5] presented a novel technique using process-disturbance data combined with a closed-loop Bode plot to evaluate the control-configuration selection for distillation columns and to predict the closed-loop product variability for the column. In all cases cited, the main objective was to obtain a faster process response when a disturbance occurred.

Hankis[6] demonstrated the disturbance propagation effect of liquid and vapor flow variations using a wave model. In fact, transition time, that is, the time required to reject or minimize the disturbance effect, is strongly associated with the successive condensation and evaporation that occurred in the column trays, resulting in internal flow variations. Therefore, proposals such as those reported by Hernández *et al.*[7] described the modifications in conventional distillation columns. The retrofit implied the incorporation of liquid or vapor recycle-streams among conventional distillation columns. Each recycle stream removes one condenser or one reboiler. The introduction of thermal links can lower the energy consumption by 40 %, which is in contrast to the conventional distillation trains that are widely used in the industry.

The use of dual control using column trays near the extremities of the column results in hydraulic delay because there is a physical limitation, that is, the distillation operation carried out with column trays required for separation is also a limitation to reduce transition time as a result of successive condensation and evaporation that occur in the trays. Owing to this, pairing studies are extensively used. On the other hand, previous studies to minimize energy supply acting in internal flows have shown that the principle of intensification in internally heat-integrated distillation columns minimizes the temperature difference between the heat input and output[8]. Based on this outcome, Marangoni and Machado[9] proposed the use of heat distribution as a strategy (named distributed control) in which a dual-temperature control was associated with a decentralized internal temperature control loop (internal column trays) as a way to minimize transition time using simple control systems (classical PID controllers). In this study, the feed temperature was evaluated as a disturbance. Unlike energy-related studies, in this case, the authors emphasized the use of an additional energy supply (heating point in tray) as a way of minimizing the time required to carry out the necessary evaporations in a column tray operation of a column. Later, Marangoni *et al.*[10] evaluated the same system for feed composition disturbances. In both cases, a reduction in transition time on the order of 1 h was observed in the operation of a column with 13 trays when used as an internal control applied simultaneously to column trays 11 and 12 that are associated with a conventional dual control.

As we know, the location of the control loop could influences the performance of the overall system. Therefore, the objective of this work was to evaluate the effect of the location of each internal control loop separately in this distributed proposed control approach, aiming to minimize transition time, in comparison with the use of conventional dual temperature control.

The major types of disturbances encountered in regulatory control of distillation columns are feed flow rate, feed composition, feed enthalpy (or temperature), reflux changes, loss of reboiler steam pressure, and column pressure. Depending on the reflux ratio used in the unity, feed temperature changes can significantly alter the vapor/liquid rates inside the column, causing changes in internal profile. This directly influences the final product composition. This disturbance can be difficult to identify because most industrial columns do not have feed temperature measurements[11]. Experimentally, it was easier to carry out temperature than composition disturbances. Also in this study, a binary system was used (water and ethanol) that allows to relate composition with temperature. For this reason, temperature disturbance was chosen to evaluate the influence of location of the internal temperature control loop on the performance of the dual temperature control.

Material and methods

The experiments were carried out in a continuous pilot unit, processing an ethanol–water mixture. The tower has 13 sieve trays that are built of steel modules, which measure 0.15 m in height and 0.20 m in diameter. The feed was loaded into tray 10 (ten), with the reboiler being on the 14th column

Table 1 – *Operational conditions used in the experiments*

Variable	Value
Ethanol feed volumetric fraction	0.20
Feed temperature (sub-cooled – ºC)	~80
Volumetric feed flow (m^3 s^{-1})	$8.34 \cdot 10^{-5}$
Column top pressure (Pa)	$1.25 \cdot 10^5$
Pressure drop (Pa)	$0.25 \cdot 10^5$
Reflux ratio (Reflux stream/Distillate)	5–8
Bottom holdup (m^3)	0.04
Accumulator holdup (m^3)	0.05

tray. Each module received a point for temperature measurement, one for sample collection, and a third for the distributed heating adaptation. For the latter, measurement was performed by means of electrical resistance measurements, with powers of up to 3.5 kW each. Details are described in the report by Werle *et al.*[12] The experimental conditions are shown in Table 1. Composition measurements were conducted during the tests, for which samples were taken from the bottom and the top products, and the amount of alcohol present was quantified using an alcoholmeter. Figure 1 shows the control configuration for the distillation tower.

Inventory control was implemented by the bottom-level control through the bottom product flow-rate adjustment; the accumulator-level control manipulated the top product flow rate and the feed flow-rate control was a function of the adjustment of the same stream flow rate. Also, the feed temperature control was implemented through the fluid flow-rate adjustment in the heat exchanger of this column tray. In this work, quality control (in this case, represented by temperature), named as conventional, was implemented by the top-column tray temperature control by means of the manipulation of the reflux flow rate; the bottom-column tray temperature control was implemented through the vapor flow rate in the heat exchanger of this column tray. When these two loops were combined with temperature control of the predefined column trays of the column by adjusting the dissipated power in the electrical resistance of the tray, we considered it as a distributed strategy.

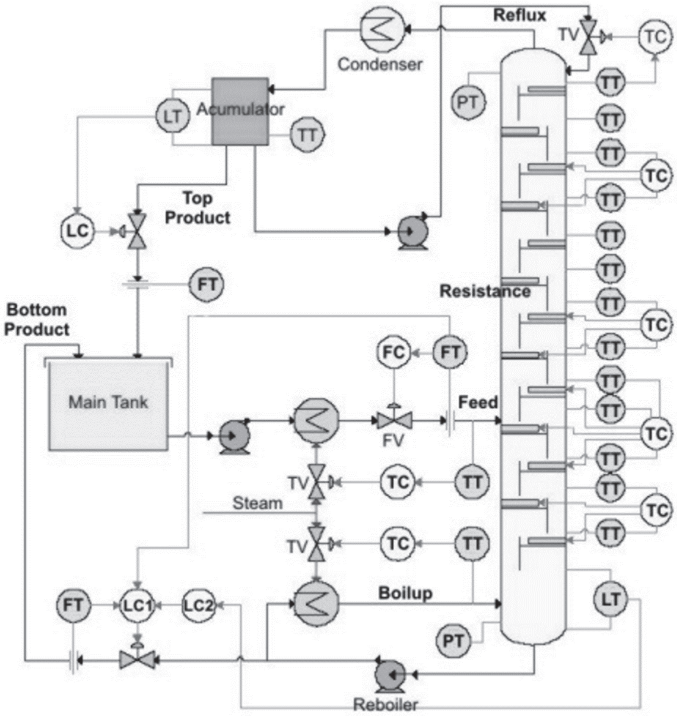

Fig. 1 – *Structure of the control loops in the distillation process*[9]

PID controllers were implemented in all cases for quality control. Conventional control was considered a multivariable system, and static decouplers were used to tune their parameters. For a distributed strategy, the third control loop was considered to be decentralized. As an initial estimate, the PID controller parameters were calculated using the criterion of the integral of time absolute error (ITAE) for regulator problems. A fine adjustment was then carried out in the plant, which was based on concepts for variations in PID controller parameters. For the distributed strategy, the same controller parameters obtained in the conventional strategy were used for the bottom- and top column tray temperature loops. For in-tray temperature controllers, the ITAE criterion was also applied to estimate the parameters, followed by fine adjustment (considering this loop decentralized from the others, i.e., with a weak interaction). It should be noted that the purpose of this study was not to develop advanced controllers, but to test a new operation and control approach. Table 2 summarizes the control parameters.

A previous study through sensitivity tests concerning the location of the column tray where the distributed strategy is applied was previously described by authors[9], who demonstrated that column trays 11 and 12 are appropriate for distributed con-

Table 2 – *PID control parameters (after fine adjustment) used for conventional and distributed system*

Controller parameter	Temperature control loop position		
	Bottom-stage	Top-stage	Intermediate-stage
Kc (K.% valve opening^{-1})	294.5	–283.0	373*
τ_I (s)	50.0	80.0	16
τ_d (s)	7.0	8.0	5

* (K.% electrical resistance power^{-1})

trol. After that, the authors used these two column trays in combination for the evaluation of the proposed control approach. Therefore, the influence of each one alone is studied. In order to compare the distributed strategy using different column trays, a disturbance in feed temperature was applied, reducing its value from 80 to 68 °C (approximately).

Results and discussion

Figure 2 illustrates the disturbance effect in the bottom temperature for the three evaluated strategies. After the disturbance, it can be seen that conventional control presents a delay of about 98 s, whereas the distributed strategy with column tray 11 takes 36 s, and with column tray 12, it is only 29 s. Using an additional column tray to supply energy for rejecting the disturbance, the negative effects on the bottom temperature were minimized in advance of 70 % when using column tray 12, and 63 % with column tray 11 compared to a conventional system. Also, more oscillations are observed when using conventional control in comparison with the distributed one, irrespective of the column tray in which the action was used. However, the use of column tray 11 for the distributed control seems to be more advantageous, as it is the least oscillatory strategy of all the studied ones.

In order to determine transition time, a calculation was made of a derivative of the bottom temperature compared with time. Thus, transition time was considered as the time when the derivative value was different from zero after the disturbance was applied. Based on this fact, it was found that conventional control for bottom temperature needed 457 s to reject the disturbance and return to the steady state, while the distributed control with column tray 12 needed only about half this time (238 s), and with column tray 11, only a quarter of the time (112 s). This evidence shows that the distributed control minimizes the transition time in temperature control of the bottom column tray.

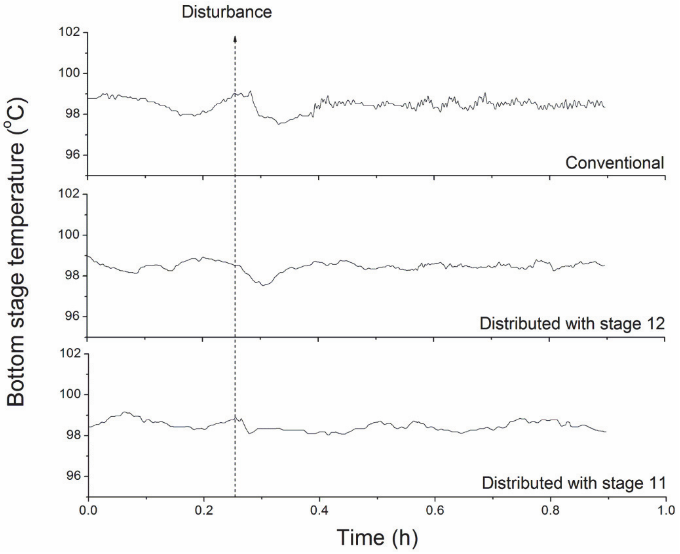

Fig. 2 – *Disturbance effect in the bottom-column tray temperature-control loop, comparing conventional and distributed strategies*

The introduced disturbance refers to a negative step in the feed temperature, which is sub-cooled. As the feed stream enters column tray 10, the introduction of a correction action in the form of a heating point just below the feed (column tray 11) reduces the impact on the lower trays by the immediate action of heating the stream. These trays (stripping section) are rich in liquid flow and have a larger holdup. Therefore, their heat changes are slow as there is more mass in the holdup. In the conventional approach, this disturbance is only rejected after the reboiler is damped (moment when the disturbance is identified), which is displayed by reducing the oscillations at the bottom temperature. For distribution approach, if the introduction of heating occurs in column tray 12, oscillations are greater than with column tray 11, as this strategy is closer to the behavior shown by conventional system than by the distributed one. Because of this aspect (oscillations), column tray 11 seems to be a better location than tray 12. But it should be noted that in both distributed cases, transition time was minimized. The control action should be carried out closest to the point of introduction of this disturbance (in this case, the feed column tray) because it was found that, in this way, the negative effects are quickly attenuated by an intermediate column tray until the heat of the reboiler is required. Thus, column tray 11 is indicated for use to compose the distributed strategy when we analyze the control loop of the bottom-column tray temperature. This result was expected, as it is logical that a corrective action just close to the disturbance would reduce transition time. However, the oscillations that are lower in column tray 11 than tray 12 are an unexpected result since the physical tray characteristics and control adjustments are same.

Figure 3 shows the control action, that is, the steam valve opening in the reboiler. All strategies had the same final valve opening after the disturbance, even with the distributed control, but their dynamics shows different behavior. In fact, the major contribution for the energy supply to minimize the disturbance comes from the reboiler. However, the heat from a column tray allows faster recuperation of the vapor phase in trays above the reboiler, and this is an immediate and temporary action, until the distillation reaches the steady state and returns to equilibrium. This could be better visualized by the curve when the distributed strategy with column

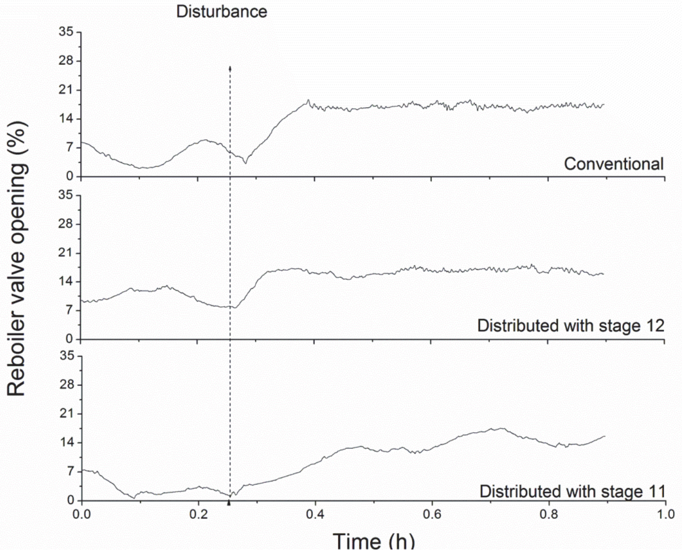

Fig. 3 – *Disturbance effect in the valve opening of bottom-column tray temperature control, comparing the conventional and distributed strategies*

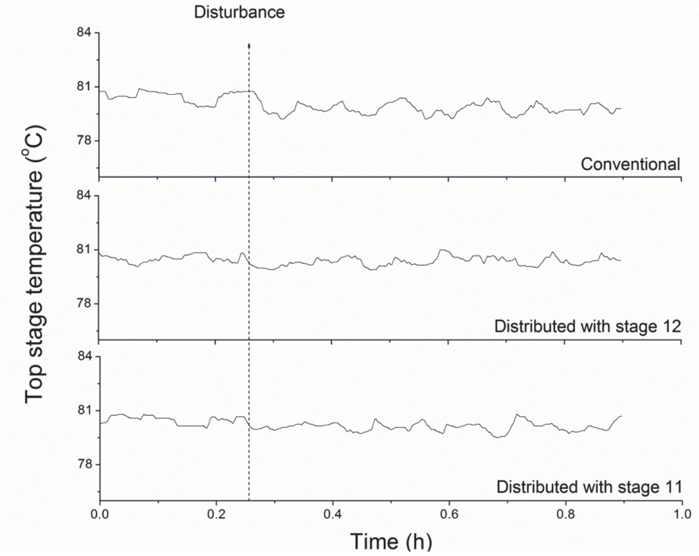

Fig. 4 – *Disturbance effect in the top-column tray temperature-control loop, comparing the conventional and distributed strategies*

tray 11 was applied. The mild slope indicates that valve opening was slowly increasing as the internal heat supply was not necessary anymore. By contrast, the strategy with column tray 12 shows a similar slope to that of the conventional system curve, as this column tray is close to reboiler, but it also shows a quick reaction from valve opening, reducing the delay visualized for conventional control.

Figure 4 shows the response of the top-column tray temperature control loop for the step-feed temperature disturbance. In this case, the approach that presents the best performance was distributed control with column tray 12, but only because this strategy shows the response that is closest to the steady state (80.5 °C). However, even for the top-column tray temperature-control loop, both distributed approaches showed better performance compared with the conventional approach.

Both distributed strategies had lower overshoots when the process was disturbed. However, the strategy with the action on the base and the top, plus column tray 12, are faster, before returning to the set-point (198 s for distributed control with column tray 12, 270 s for distributed control with column tray 11, and 306 s for conventional control). Thus, in comparison with the top column tray, the use of an internal action close to the reboiler rather than disturbance introduction seems to be more efficient.

When Figures 2 and 4 were evaluated together, aiming to determine which strategy is the most suitable, the results were contradictory when considering the bottom- and top-column tray temperatures together. The curve of the conventional approach shows the existing delay that is minimized when either distributed strategy is used for both bottom and top-column tray control loops. Considering only the bottom temperature, the strategy with column tray 12 has the fastest action; however, it presents some oscillations after a certain period. These oscillations are not attributed to noise because they are found in the conventional approach and the distributed one using column tray 12, but they are almost null when using column tray 11. In addition, as discussed before, the strategy distributed with bottom, top, and column tray 11 showed a lower overshoot, indicating the possibility that for bottom temperature control it is more advantageous to have the action distributed near the feed point where, in this case, the disturbance is applied. For the top column tray, in the same way as for the bottom-column tray temperature, it can be seen that distributed strategies also minimize the delay to the upper section of the column. However, we found that, when the distributed action was used in column tray 12, there was more proximity to the steady state than with column tray 11.

For a better analysis, the steady-state deviation (normalized error) was calculated for column trays 13 (stripping section) and 7 (rectifying section), as shown respectively in Figures 5 and 6, in order to better evaluate which heating point minimizes the transient time.

The temperature profile of column tray 13 (column tray near the reboiler) shows that all of the strategies include steady state deviations, which were not reduced as expected, because the disturbance in the feed temperature results in a decreasing column temperature profile. However, it can be seen that the strategy with the largest deviation is the conventional approach. In fact, the approaches with column tray 12 and 11 have deviations that correspond respectively to only ~58 % and 35 % of those presented by the conventional system. The temperature reduction observed in the stripping section was expected, as the disturbance applied (negative step at the feed temperature) induces this behavior. It is interesting to note that the distributed strategies make this deviation minor, indicating that the action inside the column is favorable to faster dynamics of the process.

When the behavior of the rectifying section was analyzed, as represented here by column tray 7 (column tray nearest the feed tray, rather than the top of the column), there were higher deviations from the steady state in relation to the stripping section. This is a result of the low-level holdup formed on the column trays of this section (rectifying section), which causes oscillations when the process is disturbed. The successive evaporation and condensation in the rectifying tray as a result of the control action to reject the feed disturbance provokes level oscillations in a tray with lower holdup (as in this case). This affects the temperature measurement, resulting in these observed deviations. However, it is also important to notice that same control parameters were used for both control distributed schemes (using column trays 11 and 12). This was a definition made aiming to observe only the effect of tray location in this new distributed approach. Therefore, maybe the control adjust applied was not the best option, but it allowed to analyze the proposed objective. However, even with these undesired deviations, it can still be seen that the strategy with the action distributed on column tray 11 has larger deviations from the strategy using column tray 12, which, in this case, and according to the discussion made before, indicates that when the internal control action was applied in column tray 11, all column trays (stripping and rectifying section) are influenced faster than when column tray 12 was used.

These results show that it is more appropriate to use heating points near the disturbance (in this case, column tray 11), aiming to minimize the deviations in the bottom-column tray temperature control, and the points farthest (column tray 12) from the top-column tray temperature control. Thus, it may be possible to obtain better minimization of the transient operation with the simultaneous use of the column trays in the distributed approach. In general, the responses to the extreme temperatures in the column show that the introduction of distributed control action led to the rejection of disturbance. The control became less oscillatory. As previously discussed and expected, when the temperature disturbance was applied, all temperatures decreased compared to their steady-state values. When there is intermediate action, the disturbance effect is less pronounced once the desired temperature profile has been restored. This effect can also be seen in Figure 7, where the temperature profile for column tray 11 is presented.

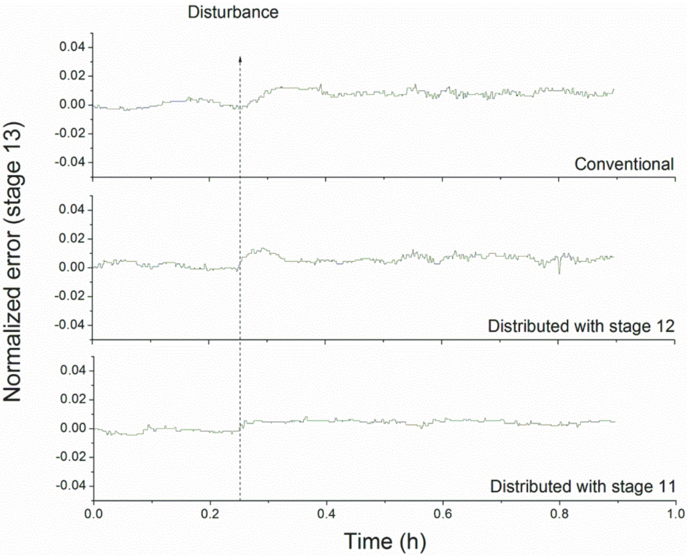

Fig. 5 – *Normalized error for column tray-13 temperature control (stripping section), comparing the conventional and distributed strategies*

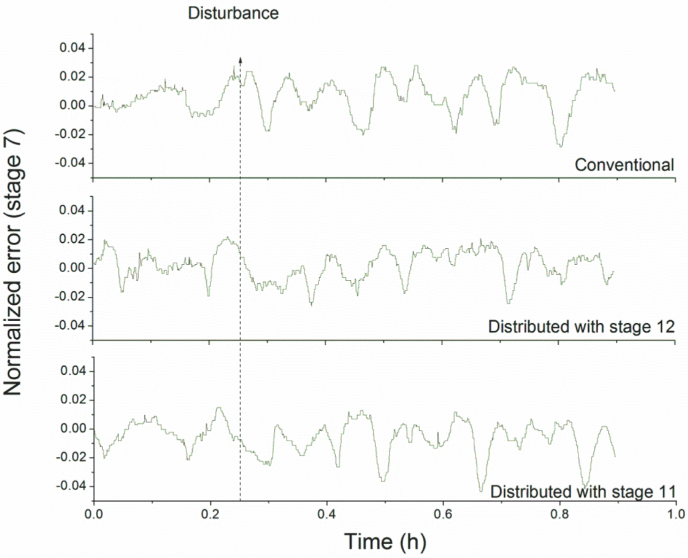

Fig. 6 – *Normalized error for column tray-7 temperature control (rectifying section), comparing the conventional and distributed strategies*

As expected, the action on column tray 11 maintained the temperature of this column tray at the set-point, because of the control loop implemented exactly in the tray. However, it is important to note the result when using the distributed control on column tray 12. This shows a better performance compared with the conventional approach, clearly illustrating the decrease in the temperatures inside

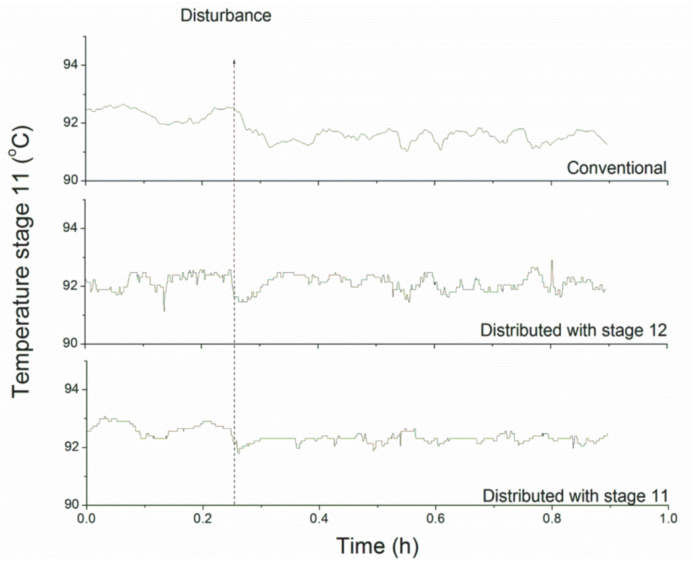

Fig. 7 – *Disturbance effect in column tray-11 temperature-control loop, comparing the conventional and distributed strategies*

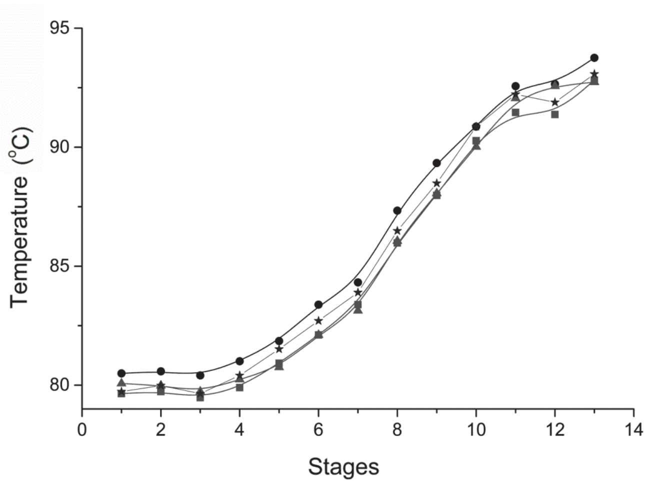

Fig. 8 – *Temperature profile along the column trays at the steady state after disturbance in the feed temperature (•), with conventional control (▪), distributed using column tray 12 (▲), and distributed using column tray 11 (★)*

the column. Based on this result, a comparison of the strategies through the analysis of the temperature profiles along the column trays was made and is shown in Figure 8.

It is desirable that the curves should remain close to the steady state; in this case, the perturbation would be completely rejected and the transient would be kept to a minimum. The curve representing the action distributed on column tray 12 keeps this behavior to column trays 13, 12, and 11. When using the strategy with action on column tray 11, the entire temperature profile is closer to the desired value, that is, the previous steady state for disturbance. Because of this behavior, we would rather use column tray 11 when the distributed strategy is used with only one internal column tray.

Conclusions

It was observed that both strategies with distributed control allow a reduction in the temperature changes caused by the applied disturbance. Thus, keeping these variables at the desired values, there is a minimization by operating outside of the specified period. This behavior was not observed with the conventional approach, in which all there was a decrease in temperatures in the internal column trays within the column. This behavior results in higher transition times than with the distributed strategy. The insertion of an internal heating point alters the vapor and liquid flows quickly when the process is disturbed, and the transient is minimized.

With respect to the location of the internal-column tray control loop, the results show that it is more appropriate to have heating points near the disturbance (in this case, column tray 11) at the bottom-column tray temperature control and points farthest (column tray 12) from the top-column tray temperature control. Thus, the decision of which column tray to use depends of the control objective, that is, if it is the bottom or top product. If both are necessary, it is interesting to combine the use of more column trays to compose the distributed control. But considering the maintenance of the entire temperature profile close to the steady state prior to disturbance as a parameter of better minimization to the disturbances effects, the strategy using column tray 11 showed better performance.

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