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Control Schemes of Hybrid Distillation-vapor Permeation Process for Ethylene/Ethane Separations

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Three control schemes based on temperature, pressure and temperature, and ratio were proposed for hybrid distillation-vapor permeation process of ethylene/ethane separation. The dynamic performances of the three control strategies were examined based on the responses to step changes of the flow rate ±5 %, temperature +2 °C and -0.032 °C. When the feed flow rate and temperature changed, fluctuation curves of ten parameters including distillate flow rate, bottom flow rate, ethylene concentration in distillate, ethane concentration in bottom, top stage pressure, top stage temperature, reflux ratio, boilup ratio, reboiler level and bottom stage temperature were compared to conform the optimal control strategy. The results show that ratio control scheme 3 is the best according to the system stability and controllability.

1. Introduction

Distillation is very important and handles more than 90 % separations in the chemical process industry (Soave and Feliu, 2002). But it is also an energy and capital-intensive process. The separation of mixtures with low relative volatilities by distillation alone requires large numbers of trays and high reflux ratios (Luyben, 2014). Finco et al. (1989) showed that distillation column for separation of propane and propylene required 160 trays and the reflux ratio 12.5. To reduce the equipment and operating cost of the separation, hybrid processes of distillation-membrane are studied as a promising alternative (Xiao et al., 2015). Stephan et al. (1995) introduced some guidelines and general rules for distillation-membrane hybrid processes. Pettersen et al. (1996) compared three hybrid membrane and distillation processes theoretically using the separation of propylene and propane as a representative case. Kookos (2003) proposed a mathematical programming methodology for the efficient optimization of distillation and membrane hybrid systems for the propylene/propane separation, the results showed that the economic potential for using hybrid systems to achieve difficult separations was important. Distillation is a constrained, coupled, nonlinear, nonstationary process and has disparate dynamic behaviour (Dutta and Rhinehart, 1999). In the last years, the detailed dynamic process models are becoming the key-tools to improve plant stability, flexibility, and controllability. And the dynamic simulation can push towards certain modifications in the unit operation and process design (Trafczynski et al., 2016). This work focuses on looking for optimal control scheme of the hybrid distillation-vapor permeation process. The research work was carried out in the following steps: (1) establishment of the hybrid process dynamic model; (2) implementation of three control schemes; (3) four kinds of disturbances are added to three control schemes, and the optimal control scheme is determined on the basis of the fluctuation curves of key parameters.

2. Dynamic simulation of hybrid process

The hybrid distillation-vapor membrane separation system was studied. And the main parameters of the hybrid process can be found in the literature (Caballero et al., 2009). The model of the vapor permeate is built with modified membrane extension in UniSim Design based on SRK thermodynamic equation. The steady state simulation results show that the model is accurate. In the dynamic simulation, controller was added in steady state model according control schemes. And in order to meet requirement of dynamic simulation, some parameters were changed and units were added. For example, (1) the temperature and pressure of the column feed were changed to -18.56 °C and 2,100 kPa; (2) a preheater was added before the membrane module; (3) a compressor was added after the residue gas; (4) a preheater was added after the permeate gas.

3. Control scheme configuration

The main control scheme of hybrid distillation-vapor permeation process is shown in the Figure 1. In the main process, the flow rate of side stream is kept at a constant, and the heat flow of heat exchanger E-101 is manipulated to control the temperature of the side stream before the membrane. The main control scheme is the same for three schemes, but the control configurations of distillation in three schemes are different. And proportional-integral-derivative (PID) control algorithm was used. The controller tuning parameters (the proportional gain, K_c; the integral gain, T_i; the derivative gain, T_d.) were determined by trial and error method.

3.1 Temperature control scheme (scheme 1 or S1)

In the distillation sub-process, the distillate flow rate and bottom flow rate are manipulated to control the condenser and reboiler level, respectively. The major feature of the configuration is the top stage temperature control. In this conventional control scheme, the reflux lag is small, and the disturbances of rectifying section are controlled timely. But heat values of the condenser and reboiler are adjusted manually which affect the stability of the process seriously. The detailed control configuration of distillation for scheme 1 is shown in Figure 2. And the PID controller tuning parameters of S1 are provided in Table 1.

Table 1: PID control parameters of three control schemes (S1, S2 and S3)

	Item	Set value	Action	K_C	T_i		Item	Set value	Action	K_C	T_i
S1	FIC-FEED	100 kmol/h	Reverse	0.1	0.2	S2	TIC-FX2	-5 ºC	Reverse	0.01	0.01
	FIC-FX1	320.9 kmol/h	Reverse	0.1	0.2		TIC-100	-27.8 ºC	Direct	0.01	0.01
	TIC-FX2	-5 ºC	Reverse	0.01	0.01						
	TIC-100	-27.8 ºC	Direct	0.01	0.01	S3*	PIC-101	2,000 kPa	Direct	1	4
	LIC-100	50%	Direct	4.00	4.00		RATO-100	273.2 kmol/h	Reverse	0.2	1
	LIC-101	50%	Direct	4.00	4.00		RATO-101	193.6 kmol/h	Reverse	0.02	10

*Values of Ratio are 4.1 and 5.8 in controllers RATO-100 and RATO-101 of S3.

3.2 Pressure and temperature control scheme (scheme 2 or S2)

In scheme 2, the sub-process of the distillation, the condenser and reboiler level control are stilled used. The heat value of the condenser is manipulated to control the top stage pressure of the distillation column, and the bottom stage temperature is adjusted by manipulating the heat flow of the reboiler. In this control scheme, heat flow of condenser and reboiler are manipulated automatically based on the column pressure and temperature. Control configuration of the sub-process is shown in Figure 3. And tuning parameters of the controllers TIC-FX2 and TIC-100 for S2 can be seen in Table 1, other controller tuning parameters are the same to S1.

3.3 Ratio control scheme (scheme 3 or S3)

The use of ratio controllers were used in scheme 3. Figure 4 shows the control structure of distillation. The reflux ratio is controlled in the top by the reflux flow rate. Condenser level is held by the distillate flow rate, and the top

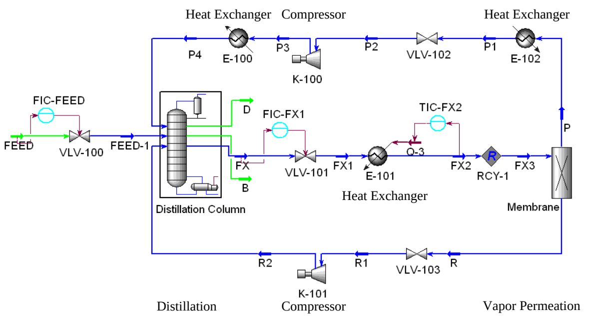

Figure 1: The main control scheme of hybrid distillation-vaper permeation process of ethylene/ethane

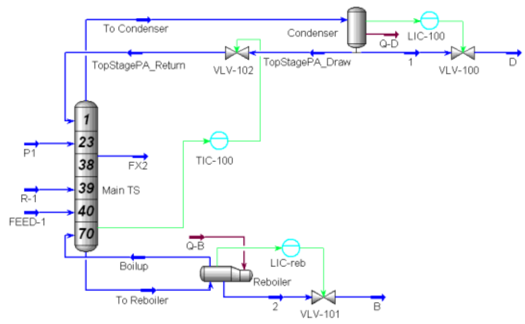

Figure 2: Sub-process configuration of temperature control (S1)

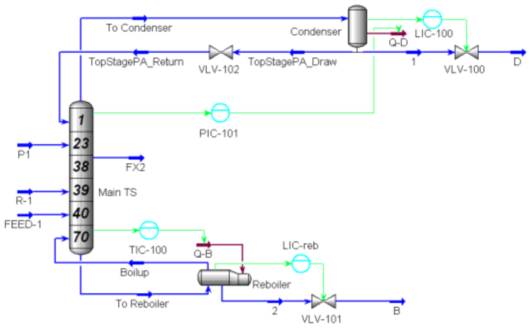

Figure 3: Sub-process configuration of pressure and temperature control (S2)

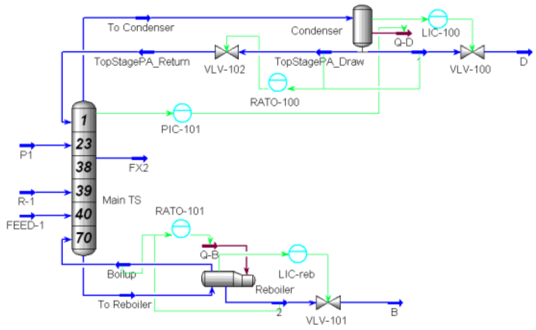

Figure 4: Sub-process configuration of ratio control (S3)

stage pressure of the distillation column is stilled controlled by the condenser heat flow. The ratio of the steam flow rate to bottom flow rate is controlled by the reboiler heat flow rate. The reboiler level is controlled by manipulating the bottom flow rate. And the tuning parameters of controllers PIC-101, RATO-100 and RATO-101 for S3 can be seen in Table 1, other controller tuning parameters are the same to S1.

4. Control strategy and results analysis

Base on the Event Scheduler in UniSim Design, the performances of the three control schemes are examined on the basis of the responses of the process to step changes of the flow rate ±5 %, temperature +2 °C and -0.032 °C (the heat value equals the value when the temperature increases 2 °C). Dynamic fluctuations of distillate flow rate, bottom flow rate, ethylene concentration in distillate, ethane concentration in bottom, top stage pressure, top stage temperature, reflux ration, reboiler ratio, Reboiler level and bottom stage temperature were studied in three control schemes.

4.1 +5 % disturbance in the feed flow

The fluctuation curves of parameters are shown in Figure 5. For the feed is in saturated gas, when the feed flow steps change of + 5%, the steam flow and pressure of the distillation column increase. In scheme 1, the condenser and reboiler levels are maintained at 50 % by manipulating the reboiler heat value manually. Running for a period of time, the distillation column reaches a new balance. During the fluctuation, the top stage temperature changes gently, and the top stage pressure stabilizes at 2015-2016 kPa. The changes of distillate flow rate, bottom flow rate, reflux ratio, reboiler level and boilup ratio show sine wave and the amplitudes decline which fulfill the ideal graphics in auto control. Ethylene concentration in distillate keeps around 0.947, but the ethane concentration in bottom still decreases at 7.5h. This shows distillation column overhead temperature control is in favor of column top production quality index. In scheme 2, top stage pressure and bottom stage temperature are controlled by manipulating condenser and reboiler heat values, respectively. When the feed flow rate increases 5 %, the top stage temperature, top stage pressure and bottom stage temperature fluctuate strongly. In scheme 3, parameters fluctuate slightly when the disturbance is added, then reach steady state. So the control scheme 3 has best stable performance.

4.2 -5 % disturbance in the feed flow

Figure 6 gives the response curves of the process when the flow rate steps change of -5%. When the feed flow steps change of -5 %, the steam flow and pressure of the distillation column decrease. In scheme 1, the condenser and reboiler levels are maintained at 50 % by manipulating the condenser heat value manually. The fluctuating performance of parameters show sine wave and the amplitudes decline. The process stability is good and used widely in industrial applications. In scheme 2, during 0.1 - 1.5 h, there is no bottom product, then the boilup ratio is infinite. Because top stage pressure and bottom stage temperature are adjusted simultaneously, gas-liquid misbalance of the distillation column results in reboiler heat value too large during 1.5 - 4.5 h, and the boilup ratio even reaches 78. Although parameter fluctuation curves stabilize at last, a long time is needed, and the curves are still fluctuating at 7.5 h. In addition, the top stage temperature, top stage pressure, reboiler level and bottom stage temperature fluctuate irregularly. In cascade control scheme 3, under the manipulation of ratio controllers, all parameters run stably.

4.3 +2 °C disturbance in feed temperature

When the system run 5 min, the feed temperature increases 2 °C, parameter fluctuation curves of three schemes were obtained. When feed temperature increases 2 °C, parameters in scheme 1 and 3 keep stability. In scheme 2, the increase of feed temperature results in high gasification rate, which result in top stage pressure.

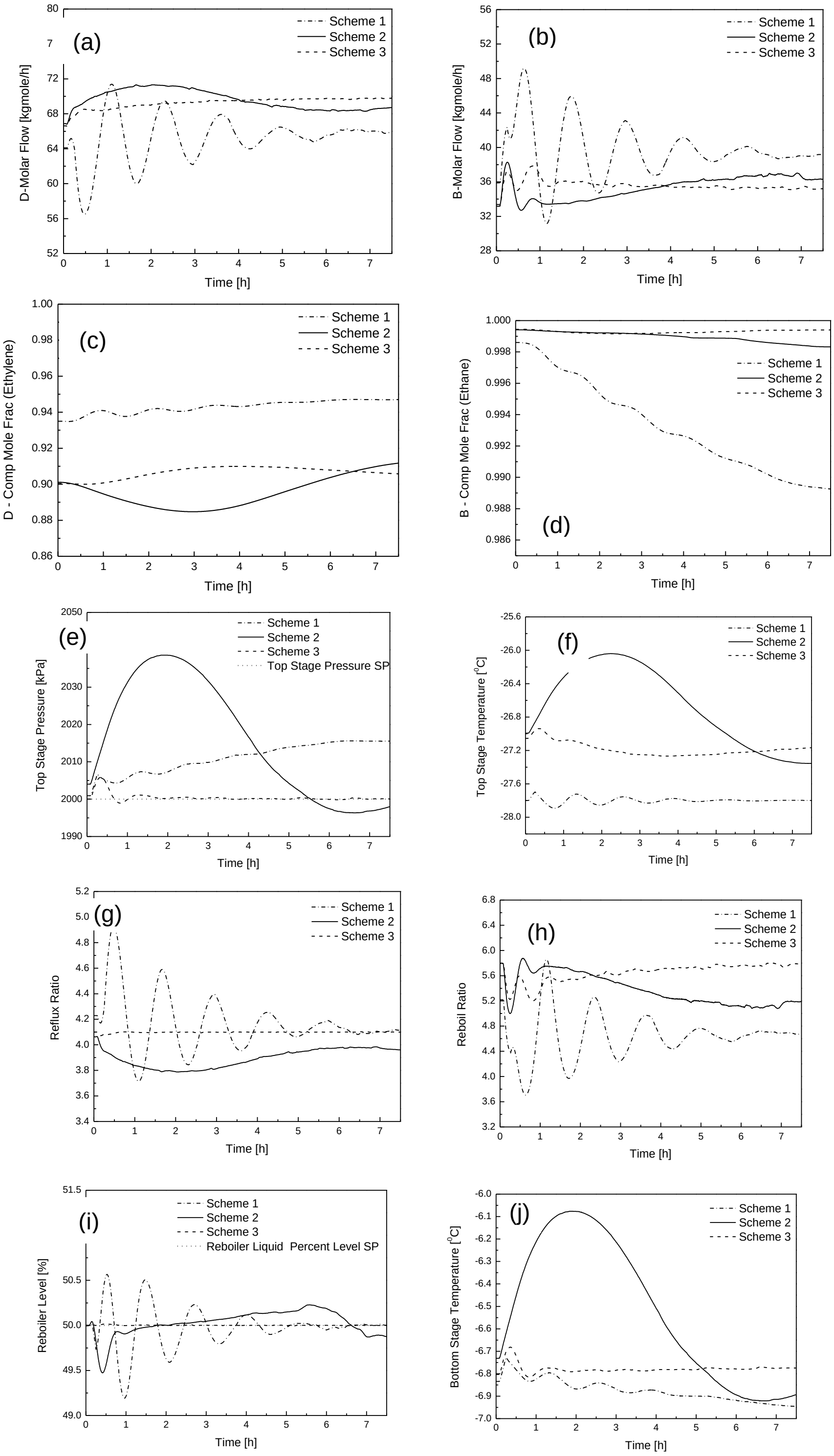

Figure 5: Parameters fluctuation curves of three control schemes for a + 5% disturbance in the feed flow rate [(a) distillate flow rate, (b) bottom flow rate, (c) ethylene concentration in distillate, (d) ethane concentration in bottom, (e) top stage pressure, (f) top stage temperature, (g) reflux ratio, (h) reboiler ratio, (i) reboiler level, (j) bottom stage temperature]

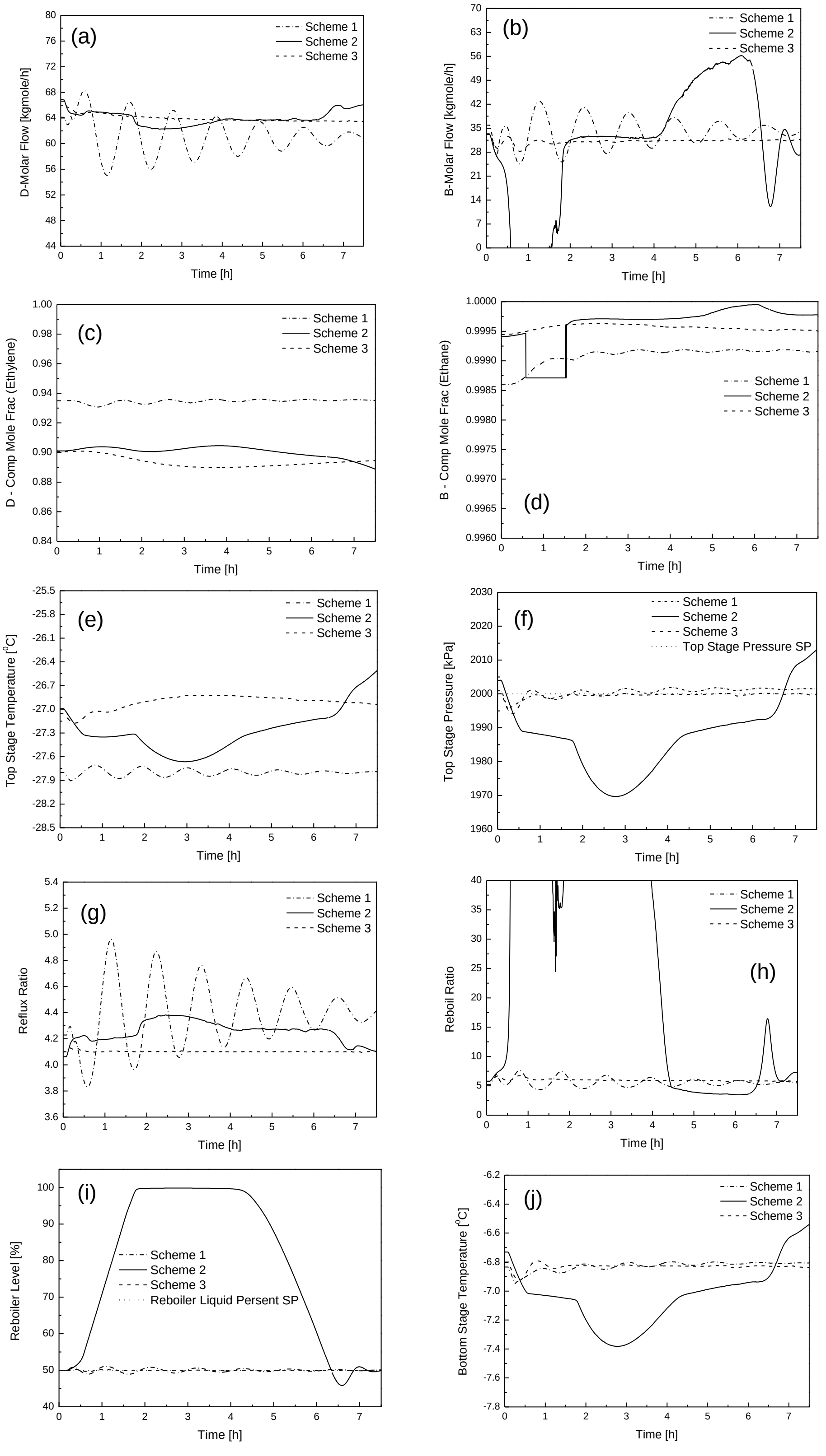

Figure 6: Parameters fluctuation curves of three control schemes for a -5 % disturbance in the feed flow rate [(a) distillate flow rate, (b) bottom flow rate, (c) ethylene concentration in distillate, (d) ethane concentration in bottom, (e) top stage pressure, (f) top stage temperature, (g) reflux ratio, (h) reboiler ratio, (i) reboiler level, (j) bottom stage temperature]

and bottom stage temperature increase further, then condenser heat value increases accordingly. With the control of pressure and temperature controller, parameters trend toward set values, but a long time is needed. When the system runs 6 h, parameter fluctuations are still obvious.

4.4 -0.032 °C disturbance in feed temperature

For the feed is in saturated gas, when the temperature decreases, feed phase state changes. Reduction of feed temperature -0.032 °C was determined according to the same heat value change when feed temperature increases 2 °C. Parameter fluctuation curves of three schemes were obtained. The results analysis are shown as follows: in scheme 1, the condenser and reboiler levels are maintained at 50 % by manipulating the reboiler heat value manually. Parameters show sine wave and the amplitudes decline, but a long time is needed to reach steady values. In scheme 2, the change of feed state leads to column top pressure and bottom temperature decrease. Parameters trend to set values with the help of ratio controllers, but it will waste a long time. Parameters keep stability in scheme 3.

In fact, for these three control schemes, scheme 1 and 2 are direct parameter control and simple, but the control scheme 3 is cascade control and complex. Although the scheme 3 is more sensitive and shorter reaction time than scheme 1 and 2, scheme 1 and 2 are more used in process industry.

5. Conclusions

Three different control schemes of hybrid distillation-vapor permeation processes were provided in this work. The performance of the three control strategies were examined on the basis of the responses to step changes of the flow rate and temperature of feed. Dynamic fluctuations curves of 10 parameters were compared in three control schemes. The results show that the stability and controllability of scheme 3 is the best, scheme 1 took the second place was achieved. On the other hand, the control configuration of scheme 1 is simpler, and condenser and reboiler heat values are manipulated manually which response the system timely. So the control strategy of scheme 1 is widely used in the field of industrial applications.

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