Study of the Control Systems of a Distillation Process Equipped with Heat Pump

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The paper presents the results of the researches on the modelling and simulation of the propylene-propane mixture distillation process equipped with heat pump. Industrial data regarding the process structure, operating data and control structure are presented. Modelling and simulation of the process was accomplished using the resources of the Unisim Design simulator. Because the simulator does not include a mathematical model associated with the distillation process equipped with heat pump, the distillation column model was replaced with the Reboiled Absorber model from the simulation environment library. An analysis of the multivariable character of the distillation process revealed discrepancies between the structure determined by the Relative Gain Array analysis and the industrial control structure. The design of the control systems requires dynamic simulation of the process, so the authors' research was focused on the dynamic simulation of the absorption process. The obtained dynamic model was the starting point for testing the propylene quality control system. Finally, the optimal operating conditions for this process were analyzed.

Keywords: distillation process with heat pump, absorption process, Unisim Design, dynamic simulation

The distillation process equipped with heat pump represents a relatively new approach. The similarity between the distillation process and the absorption process with heat pump was described in [1]. The paper represents a strong reference in the field of distillation process simulation. The used simulation model is an absorption column to which the mathematical models for the compressor, detent valves, vaporizer vessel and condenser have been added. The Simulation Diagram was made with Aspen HYSYS simulator and was used to verify the steady-state functionality of the proposed process structure. The paper contains a comparative analysis of the distillation process versus the absorption process.

Another fundamental reference on the study of the absorption process with heat pump is [2]. In the paper, the distillation process and the absorption process with heat pump were simulated in steady-state. For both processes, HYSYS simulation environment was used. The obtained results were used to demonstrate the efficiency of the heat pump absorption process.

Aspects regarding the control of the distillation processes are presented in [3]. Although the study refers to the distillation processes, a control structure for the distillation columns equipped with heat pump is presented in the article. One of the addressed issues is the system's degrees of freedom. The article suggests the connection between the compressor discharge pressure and the reflux vessel pressure, considered as a vaporizer vessel. The influence of compressor speed on the process has been analyzed in the past by Shinskey [4]. Analyzing this reference and industrial data and practice, the authors concluded that safe compressor operation is only possible at constant load and speed.

The authors made their own research in the field of heat pumps, modelling, simulation and control of distillation columns. Thus, aspects regarding the modelling and simulation of the heat pump were treated in [5]. The modelling and simulation of the propylene-propane distillation process is presented in [6, 7]. The authors' research continued with the study of the control systems associated with both the distillation and absorption columns with heat pump [7- 9]. Other research aimed the dynamic modelling and simulation techniques of the distillation process [10].

In this context, the objectives of this paper are as follows:

-study of the industrial aspects of the distillation process equipped with heat pump;

- seady-state and dynamic simulation of the absorption process;

- analyzing the multivariable character of the industrial process of propylene-propane distillation;

- analyzing the possibility of optimal control of the absorption process.

Distillation column with heat pump

A.Industrial Distillation Column with Heat Pump

The propylene-propane separation process is the main source of raw material for polypropylene and plastics. The process is known and studied, is extremely complex, its distributed and multivariable nature being two main characteristics of the process [8].

The high energy consumption of the distillation process is the main disadvantage, becoming extremely important for mixtures with low relative volatility, such as the propylene-propane mixture. In this context, the heat pump distillation column and the thermally integrated distillation column represent heat recovery solutions for increasing the efficiency of the distillation process [11]. The authors have studied the propylene-propane distillation process with heat pump. A synthetic representation of this process is shown in figure 1.

B.Industrial Data

The authors carried out industrial measurements associated with a propylene-propane separation column with heat pump from a refinery. The operating data are presented in table 1. There were selected 23 data sets corresponding to an average operating point of a day. For each operating parameter, average value and dispersion were calculated. The average values will be used to define an average operating point of the column. Standard

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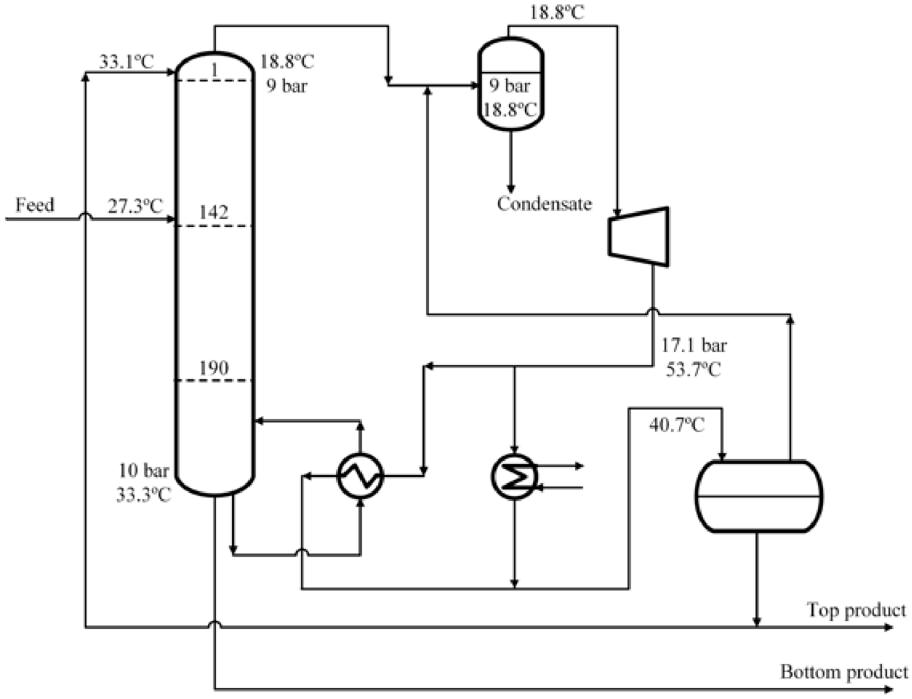

Fig. 1 Distillation column with heat pump

deviation is used to characterize the current operating mode of the column. The small values of the standard deviation reflect a quasi-stationary operating regime. Within this regime, the only notable variations are generated by the bottom product and propylene to condenser flowrates. The first flowrate is used to close the material balance at the bottom of the column and the second flowrate to control the pressure in the reflux drum. Since the concentration of propylene in distillate is constant and the feed rate is also constant, it can be appreciated that under the existing operating conditions the current control structure is suitable for control of the propylene concentration in distillate.

Process simulation

The simulation of the distillation process with heat pump is difficult due to the lack of the process mathematical model within the options offered by current simulators. The authors' research has identified the possibility of replacing the distillation column model with the model of an absorption column [6, 7].

A.Steady State Process Simulation

The heat pump can be modeled using the models available in the simulator, respectively the compressor, the condenser and the reflux drum. Results on steady-state simulation of a distillation column with heat pump are

Table 1
DISTILLATION COLUMN EXPERIMENTAL DATA

Day		Feed [m^3/h]	Reflux [m^3/h]	Bottom [m^3/h]	Propylene to reboiler [kg/h]	Propylene to condenser [kg/h]	Distillate [m^3/h]	Conc. of propylene in distillate (wt %)
1		71.93	608.40	21.20	158003	37859	40.24	99.69
2		70.08	612.71	19.02	161654	36474	40.81	99.65
3		70.94	593.81	19.85	156433	40682	40.67	99.65
4		70.08	576.07	20.60	153916	36712	39.32	99.75
5		70.53	583.80	20.36	153985	39407	40.08	99.67
6		72.85	593.09	22.16	156914	39638	40.45	99.74
7		70.09	529.90	19.11	157941	38282	40.92	99.68
8		74.45	599.18	21.46	156749	43102	42.27	99.66
9		72.49	591.90	21.30	154246	41649	40.86	99.64
10		73.66	605.06	21.13	154732	45619	42.19	99.66
11		71.02	602.86	19.14	155576	43772	41.68	99.70
12		69.86	599.19	18.32	155243	43321	41.36	99.68
13		66.06	588.56	17.72	151834	41157	38.67	99.73
14		68.08	594.57	18.47	154423	41228	39.76	99.72
15		64.51	598.43	16.77	151659	44350	38.41	99.64
16		63.96	583.63	16.99	150171	41613	37.83	99.69
17		70.92	601.60	19.50	154649	43802	41.62	99.68
18		65.24	583.54	18.34	150783	40811	38.72	99.67
19		67.49	602.13	17.92	155936	42716	40.86	99.67
20		72.34	613.30	20.04	159654	42451	41.82	99.70
21		69.72	613.59	19.08	157323	42584	40.94	99.67
22		71.25	615.43	20.71	158298	44364	40.98	99.64
23		71.08	615.63	19.98	156481	44690	41.49	99.64
Medium value		69.94	595.92	19.52	155504	41577	40.51	99.67
Standard deviation		0.57	3.72	0.30	569	522	0.25	0.006
	%	0.81	0.62	1.53	0.36	1.25	0.61	0.006

presented in [7]. In the paper, the authors have successfully replaced the distillation column model with the Reboiled Absorber model completed with the heat pump components. The validation of the new simulation model was accomplished by comparing the results obtained for the operation of the two processes under the same conditions. A suggestive image is shown in figure 2.

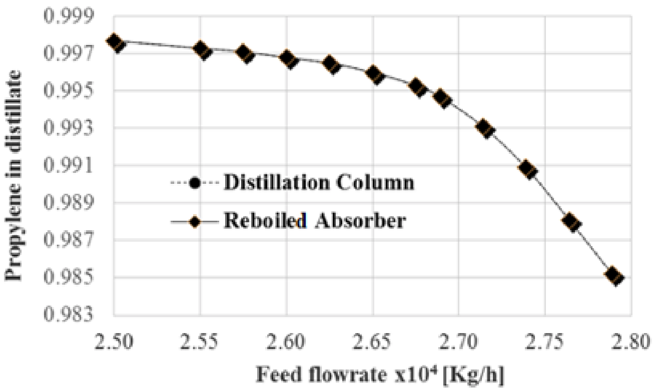

Fig. 2 Validation of the Reboiled Absorber model used to simulate the distillation column with heat pump [7]

B.Process Multivariable Character Analysis

By its nature, the distillation process is a 2x2 multivariable system. The process input variables are the commands used for quality control, and the output variables are represented by the composition of the distilled product, x_D, and the bottom product composition, x_B.

One of the methods of analyzing and designing multivariable control structures is the Relative Gain Array (RGA), used as a way of determining steady-state interactions between the commands and process outputs [12]. By choosing the best combinations of commands, it can be obtain a control structure with low interactions compared to other possible structures. For distillation processes treated as multivariable systems for which is necessary to control the quality of the distillate and the bottom product, predictive control or neural network control are good options. In the case of the studied distillation column, quality conditions are imposed only on the distillate, which makes the robust control the most appropriate solution for control the quality of the separate products. A study on robust control of a propylene-propane separation column is presented in [8].

In the following there are presented results on the selection of most suitable pair of commands associated with the distillation column with heat pump. The steady-state regime considered as the reference point is defined in table 2. The control pairs used to control the compositions of the distillate and the bottom product and analyzed in this paper are: reflux flowrate - bottom product flowrate (L-B), reflux flowrate - vapor flowrate in the column (L-V) and distillate flowrate - vapor flowrate (D-V).

Table 2

DISTILLATION COLUMN REFERENCE DATA

Characteristic	Measurement units	Values
Feed flowrate	Kg/h	2.5×10^5
Distillate flowrate	Kg/h	1.778×10^4
Reflux flowrate	Kg/h	3×10^5
Bottom product flowrate	Kg/h	7300
Concentration of propylene in bottom product	-	0.051
Boilup flowrate	Kg/h	3.113×10^5
Feed temperature	°C	26.12
Feed pressure	KPa	1000
Q reboiler	KJ/h	1.137×10^8
Q condenser	KJ/h	1.046×10^8

The process was simulated using Unisim Design, and the obtained results allowed to calculate the elements of the RGA (table 3).

Table 3

RGA VALUES

Feed flowrate [kg/h]	Pairs of commands		
	L-B	L-V	D-V
2.5×10^4	1	2115	0.04
2.65×10^4	2	2596	0.01
2.78×10^4	2	X	X

Analysis of the RGA elements indicates that the smallest interaction is obtained when using the L-B command pair. The other pairs of commands lead to extremely high interactions, which eliminates the possibility of using these pairs of commands to control the quality of the separated products of the distillation column. The variation in feed flowrate leads to changes in RGA but the relationship between pairs remains unchanged. The RGA is not the only element considered in multivariable process character analysis. In this case, the problems related to the stable operation of the compressor are essential. For operational safety reasons, the compressor speed must remain constant, which implies a constant load, that is, no variation in the vapor flow used as a thermal agent at the column reboiler. This constraint makes the L-V command pair suitable for product quality control, which theoretically would ensure the compressor's safe operation.

Another element considered in the multivariable process character analysis is related to the robustness of the product quality control structure [13]. For the studied column, the aim of the control is to obtain the distillate at a concentration of 99.99% propylene. In this case, the control of the products quality is reduced only to the control of the distillate quality, objective achieved by the implementation of a monovariable control system. The structure of the automatic system is shown in figure 3.

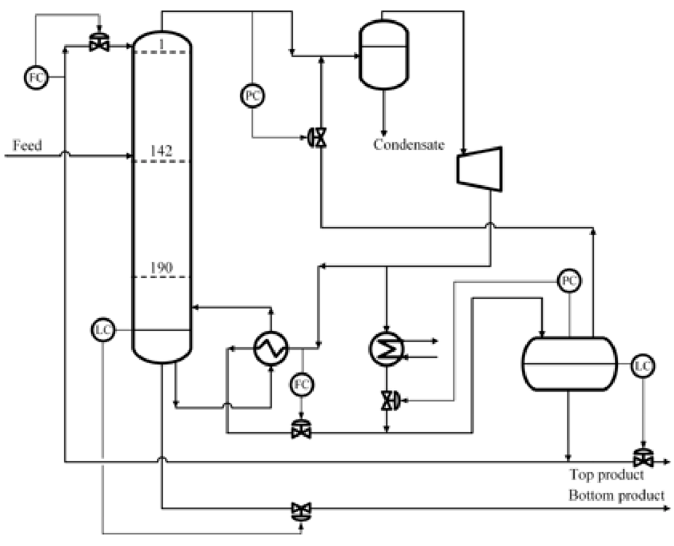

Fig. 3 Distillation column control structure

C.Dynamic modelling and simulation

Dynamic modelling and simulation of distillation columns using Unisim Design simulator, has been studied by authors and presented extensively in [10]. In this case, the steps to be taken are the following (fig. 4):

a)Steady-state simulation of the column and obtaining an initial steady-state of the process.

b)Feed stream configuration.

c)Holdup configuration for the distillation column.

d)Dynamic model verification using Dynamic Assistant.

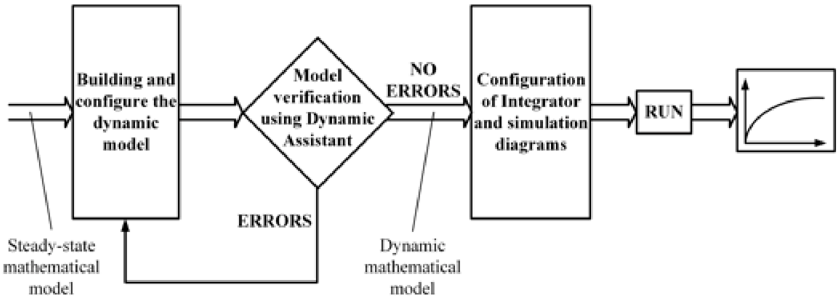

Fig. 4 Dynamic model configuration using Unisim Design [10]

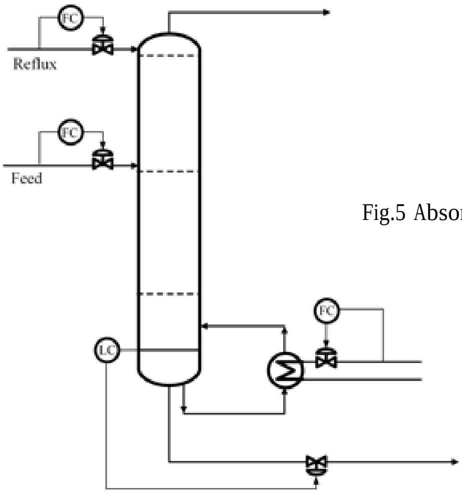

Fig.5 Absorption column

The research carried out so far has focused on the dynamic simulation of the absorption column shown in figure 5.

The design data presented in table 2 are used to simulate the steady state of the absorption column. To control the feed flowrate and reflux flowrate, control valves are implemented. The procedure involves disconnecting the stream to the absorption column, inserting the control valve, setting it up, and connecting the new stream to the absorption column. One of the requirements of the Unisim Design simulator is that the value of the control valve downstream pressure to be equal to the pressure in the column corresponding to the feed tray. This action involves a new configuration of the pressure profile of the column. A new challenge is the selection of the process variable to be controlled. In this respect, the *Standard Ideal Liquid Volume Flow* variable associated with the flow will be selected. For the controlling element, *Actuator desired Position* variable is selected, this variable being associated with the control valve object from the flowrate control system. As a result of these operations, the *Dynamic Assistant* function will reflect the errors found in the simulation configuration up to this point, (fig. 6).

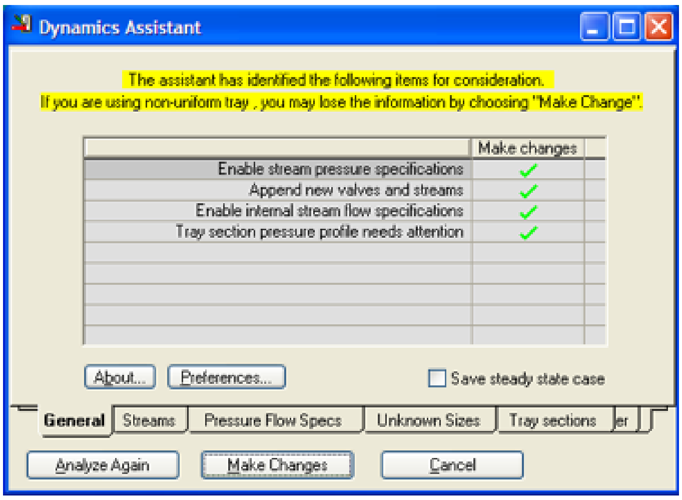

Fig. 6. Dynamic Assistant function after feed flowrate control systems implementation

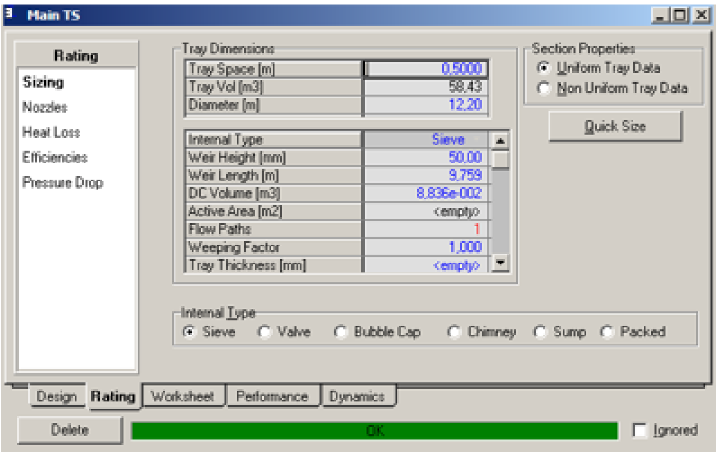

Fig. 7 Reconfiguration of the absorption column according to the preliminary results obtained with the Dynamic Assistant

The first error, *Enable stream pressure specifications*, is eliminated by configuring the *Active* option of the feed stream pressure in the *Dynamic - Spec* command group.

The second error, *Append new valves and streams*, involves the introduction of control systems with control valves for the *Distillate* and *Bottom* flows. The mechanism is similar to the one used for feed and reflux of the column. Thus, control valves are introduced, the column top pressure control system and the column level control system are built. For the two output streams of the absorption column it is necessary to activate the *Active* specification in the *Dynamic - Spec* command group.

After this configuration stage remains an error, indicating that the pressure drop on the calculated steady-state absorption column differs from that estimated in dynamic mode. To eliminate this error, in the *Dynamic Assistant* menu, select *Tools / Utilities / Tray sizing*. From the last window we get the values for tray space, diameter, weir length, weir height calculated in dynamic mode. These values are loaded manually in the *Main TS / Rating menu*, figure 7. At this time, all dynamic simulation conditions are met, and the *Dynamic Assistant* is not reporting any errors.

The control structure implemented so far lacks the thermal load control system. Since heat load is not a material flow, it is necessary to define all the variables that are used in this control system. The controlled variable *PV* is associated with the *Flowsheet T-100 / Q reboiler* object / *Heat Flow* variable. The controlling element is selected from the *Flowsheet T-100 / Q reboiler* object / *Control Valve* variable. The results obtained by simulation indicate a thermal load of 2.158 x 10^7 Kcal/h, leading to a theoretical maximum value of the thermal load of 4.5 x 10^7 Kcal/h (about twice the value associated with the reference state).

Figure 8 is the final form of the absorption column dynamic simulation diagram. The following control systems are implemented: feed flowrate, reflux flowrate, column bottom level, reboiler thermal load. The dynamic simulation program is tested in order to tune the PI

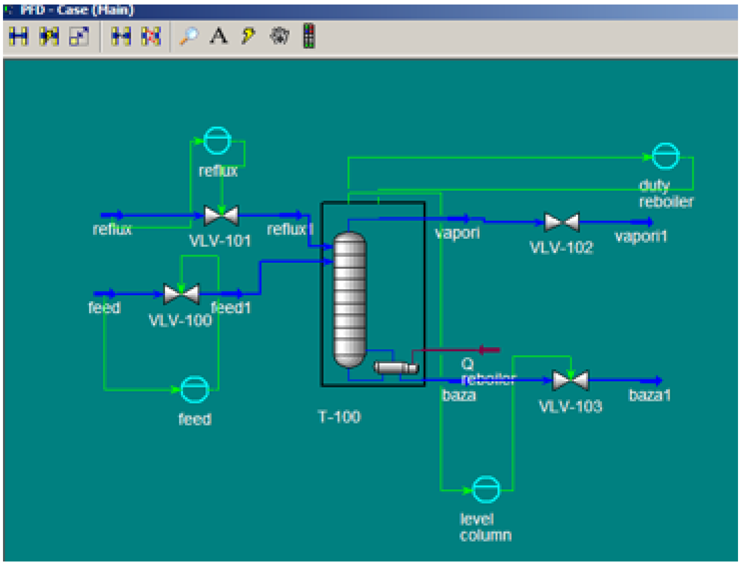

Fig. 8 Absorption column dynamic simulation diagram

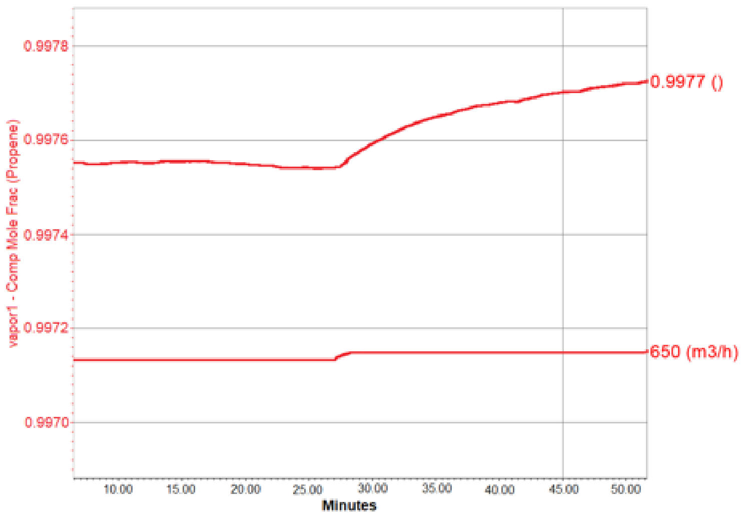

Fig. 9 Dynamics of propylene concentration in top product at reflux flowrate change

(Proportional-Integral) controllers from the control structure. After this step, the dynamic sensitivity of the outputs to step variation of the commands and disturbances of the column can be studied. Figure 9 shows the influence of the reflux flowrate on the propylene composition in the top product, for a variation of the reflux flowrate from 560 m^3/h to 650 m^3/h.

Optimal operation

Optimal control allows process operation regimes that lead both to the required specifications and minimize production costs. Authors' experience in this area is significant. Thus, for the distillation processes, the authors have developed optimal control systems that have been tested industrially [8, 14].

For the absorption processes, the authors have identified the possibility of optimal control only for the absorption process characterized by an extremely restrictive quality specification [15]. In this case, the minimization of the absorber flowrate is implemented with a step-by-step extremal regulator, as the feed flowrate is the main process disturbance. If the quality specification is not restrictive and the feed flowrate is a major disturbance, the internal model control systems are recommended [16].

For the absorption process with heat pump, the optimal control implies the study of the static characteristics of the process. Figure 10 shows the connection between the reboiler duty and reflux flowrate, the decrease of the reflux flowrate leading to the decrease of the steam flowrate and, implicitly, the decrease of the energy consumed by the compressor. The reduction of the reflux flowrate has

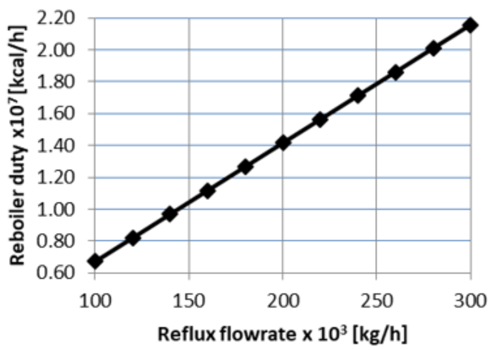

Fig. 10 Reboiler duty vs. reflux flowrate

negative effects on the quality of the top product, namely the concentration of propylene in the vapors from the top of the column, figure 11.

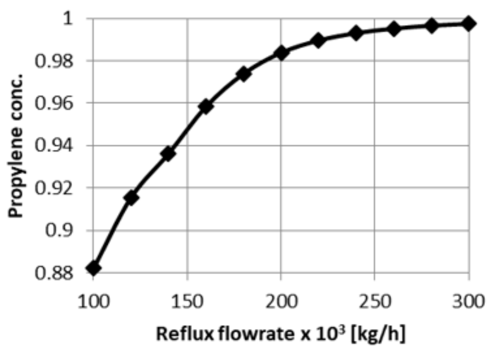

Fig. 11 Top propylene concentration vs. reflux flowrate

Given that the top product quality restriction is 0.9950 propylene and corroborating the two static characteristics shown in figures 10 and 11, a minimum reflux flowrate of 266 x 10^3 kg/h is obtained. The operation of the column at this value of the reflux flowrate leads to a minimum energy consumption of the compressor.

Conclusions

The paper presents a synthesis of the most important results in the field of modeling and simulation of the propylene-propane distillation process with heat pump.

The first research direction is represented by the study of the industrial distillation plant with heat pump. The study is completed by a set of industrial data, particularly valuable for any research in this field. Using the industrial data, the column was studied from the point of view of commands that ensure the best natural decoupling of the product quality control loops.

The second research direction was dedicated to modeling and simulating of the process. The resulting conclusions were as follows:

-The propylene-propane distillation column is simulated without difficulty using the Distillation Column model from Unisim Design simulator, the obtained results can be used as a comparison basis;

-The distillation column equipped with heat pump can be simulated only if instead of the Distillation Column model, the Reboiled Absorber model is used;

-The simulation of the two processes under the same operating conditions generated identical results, which validates the proposed Reboiled Absorber model for simulating the distillation column with heat pump;

-Because of the process complexity, the dynamic modeling and simulation of the distillation column equipped with heat pump could not yet be achieved. In the current phase, only the simulation of an isolated absorption column was realized, the mathematical model of the column being Reboiled Absorber model from Unisim Design library.

The third research direction focused on the control methods for the propylene-propane distillation column equipped with heat pump. The quality restrictions imposed on the distillate as well as the non-linear characteristics of the process led to the need to implement an optimal quality control system for distillate, based on the use of an extremal controller.

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