Abstract – This work presents the authors’ research on heat pumps together with a thorough investigation of their usage within distillation columns. The full spectrum of heat pumps is analyzed pointing out for each the pros and cons. A special emphasis is given to the analysis of the control structures that are associated to both classical distillation processes and heat pumps. A set of conclusions is drawn regarding the problem of an automatic control of a distillation column that is equipped with a heat pump.

Keywords - distillation column, heat pump, quality control system, pressure control system

I. INTRODUCTION

The distillation process represents the most widely employed method of separation that is used in a major part of the world’s oil plants, in petrochemical, as well as in chemical industry facilities. The main disadvantage of this method is that it employs a high energy cost per process, which becomes very significant especially for compounds with relatively low volatilities, such as the propane-propylene mixture.

The heat-pumped and the thermal-integrated distillation columns are two distinct processes that improved the energetic yield of the classical distillation, by implementing a technological solution that is based on the retrieval of the dispersed heat that occurs during the distillation process [1].

The most widely used distillation processes are: classical distillation columns, thermal-integrated distillation columns with heat retrieval, and heat-pumped distillation columns.

The heat-pumped distillation columns have been successfully applied in the industry by reducing the operational costs with more than 15% [2]. This technique shows an especially high energy yield when there is a significant heat transfer between the reboiler and the small work input condenser, proving to be a good solution for reducing the energy demands of the process [3]. Several research papers analyzed and compared the heat-pumped distillation column performances against other types of distillation processes, such as conventional columns or thermal-integrated distillation columns. A significant reduction of the operational costs was shown to take place for the separation of the following mixtures: isopropanol-water, ethyl-benzene-styrene, and propane-propylene [4]. The usage of heat pumps at the propane-propylene separation distillation columns promoted for all analyzed cases lower total operational costs when compared against the conventional distillation methods [5]. An optimal design of a heat pump-based propane-propylene distillation column leads to a 37% reduction of the annual operational costs [6, 7].

The use of a heat pump can reduce the operational costs of a distillation column due to the fact that the compressor’s mechanical work allows for a much more significant heat transfer (between the vapors and the distillation column’s reboiler) to take place when compared with the classical distillation column case. We should note that whereas the compressor is an essential element of the heat pump system, it poses, however, a very high operational demand.

This work focuses on the study of heat pumps and their usage within distillation columns and their associated control systems.

II. HOW TO USE THE HEAT PUMP FOR THE DISTILLATION PROCESS

A. Types of the Heat pumps

The overhead vapors that leave the heat-pumped distillation column are, in a first phase, compressed (leading to a temperature increase), to subsequently follow a heat exchange that takes place in the column’s reboiler, and, finally, they condense. The heat pumps are used to transfer heat from a colder vapor source to a hotter medium by increasing the vapor pressure by the means of a compressor. The heat-pumped systems can be classified as closed-loop and opened-loop heat pumps.

1) Heat pump in closed loop. A closed loop heat pump uses an external fluid in order to absorb the heat from the hot source and transfer it to the cold or sink source, as shown in Figure 1. The fluid undergoes the following transformations:

a) The liquid is vaporized at a low pressure by letting in the heat from the heat source (from a to b).

b) The vapors are highly compressed by using a compressor (from b to c).
c) The fluid transfers heat to a cold/sink source (from c to e).

d) The fluid is liquefied by expansion through an expansion valve (from e to a).

Figure 1 The schematic of a closed loop heat pump

We should notice that for a closed loop heat pump system, both thermal duty of the condenser, as well as the fluid debit flow are highly correlated with the thermal load of the vaporizer. Any debit flow or compressor load change should be prevented as this structure cannot properly work with variable thermal loads [8].

2) Heat pump in opened loop. An open loop heat pump takes advantage of the process’s own fluid, and can use it also as a thermal cycle fluid. The design of an opened loop heat pump allows achieving a thermal flux that can be used to heat up and/or to vaporize another flux of the process. Figure 2 shows the schematics of an opened loop heat pump.

Figure 2 The schematic of an opened loop heat pump

The following physical processes undergo in the above structure:
1) The heat pump receives the process fluid in a vapor state (state a).
2) The compressor increases the fluid process’s pressure (state b).
3) The process fluid heats up a secondary fluid that is associated to the distillation column.
4) The process fluid cools off and partially or totally condenses.
5) The non-condensed part of the mixture is recirculated towards the intake of the compressor, while the liquid part is used in the distillation process.

The use of a heat pump can reduce the operational costs of a distillation column due to the fact that the compressor’s mechanical work allows for a much more significant heat transfer (between the vapors and the distillation column’s reboiler) to take place when compared with the classical distillation column case. We should note that whereas the compressor is an essential element of the heat pump system, it poses, however, a very high operational demand.

B. Characterization of distillation processes that use opened loop heat pumps

Heat pump usage at a distillation process is only possible if the temperature difference between the bottom and the top of the distillation column is small. That is the exact situation that happens with mixtures whose components have similar boiling points. Here, we should point out that such separations, having relative volatility values close to 1, must use a high reflux ratio. Therefore, all internal fluxes (reflux \( L \) and vapor flux \( V \)) must be high, whereas all column input and output fluxes (feed \( F \), bottom product \( B \), and distilled product \( D \)) must be, in comparison, rather low [8].

The process of compressing the vapor flux insides the distillation column constitutes an opened loop heat pump system. Figure 3 presents basic schematics of a heat-pumped distillation column [8] that uses the following abbreviations: 1 – distillation column; 2 – compressor; 3 – heat exchanger that works as reboiler/condenser; 4 – expansion valve.

The economical advantages of using the heat pump system are influenced by several parameters, such as, column pressure, reflux ratio, feed flowrate, number of plates, column pressure loss. In addition, the relative cost of electrical energy used for powering the heat pump is another important factor that influences the cost-effectiveness of the heat pump application [9].

C. Opened vs. closed loop heat pump comparison

A thorough literature research has allowed the authors to build up a comprehensive synthesis of the behavior of the previously described types of heat pumps. As a result, the closed loop heat-pumped distillation column is characterized by the following:

- Variable compressor workload that depends on the condensed vapor flow and the thermal workload of the reboiler.
A rigid relationship between the condenser workload and the reboiler workload, which strips of efficiency the action of any quality control system of the separation products in the distillation column.

The existence of two heat exchange systems (condenser and reboiler).

The distillation column with opened loop heat pump is characterized by the following:

Variable compressor workload that depends on the condensed vapor flow and the thermal workload of the reboiler.

The usage of a single heat exchanger, that plays both the condenser’s and the reboiler’s function.

The elimination or the reduction of the fluid used in the thermal cycle.

Decoupling between the reboiler’s workload and the vapor condensation process. That will contribute to a good performance of the quality control systems of the separation products in the distillation column.

D. The performance of the heat-pumped systems

The performance of a heat pump is given by the performance coefficient (PCO), which is defined as the ratio between the thermal load (Q) transferred to the pump heat and the power (W) consumed by the compressor

\[ PCO = \frac{Q}{W} \]  

A greater PCO value means that the heat-pumped system is running more efficiently. The following well-established thermodynamic relationship between the Carnot ideal heat engine efficiency and the efficiency of any other heat pump holds true [10]

\[ \frac{Q}{W} = \frac{1}{\eta_{Carnot}} = \frac{T_c}{T_r - T_c} \]  

where Q is the thermal load of the reboiler, W is the power used by the compressor, \( \eta_{Carnot} \) is the efficiency of the Carnot ideal heat engine, \( T_r \) is the reboiler’s temperature, \( T_c \) is the condenser’s temperature.

According to [10], the usage of a heat pump is recommended when POC is greater than 10.

IIII. QUALITY CONTROL OF THE SEPARATION PRODUCTS PRODUCED IN THERMAL-PUMPED DISTILLATION COLUMNS

The automatic control systems used for quality check of the resulted separation products generally depend on the following factors:

Quality product(s) specifications.

Number of automatic control systems used for quality check as imposed by the nature of the process.

The commands used for the control systems for quality check.

Chemical gauge/transducers usage.

The requirements for system control imposed by the usage of a compressor, as an integral part of the heat pump.

In the following, we will present some aspects of the control systems specific to an industrial distillation propylene-propane heat-pumped column.

A. Number of automatic control systems for quality check, as imposed by the nature of the process

The distillation process is, by its own nature, a multivariable system, of 2x2 types, as presented in Figure 4. The inputs of the process (\( U_1 \) and \( U_2 \)) are the commands that are used for quality control, whereas the outputs (\( x_D \) and \( x_B \)) represent the chemical composition of the distilled product, and namely, of the product found at the base of the distillation column.

In principle, one can identify two automation solutions. The first one points to a simultaneous control check of both distillation product and column product found at the column base. This case requires the implementation of a multivariable control system.

The second solution deals with the control check of only one product, which can either be the distillate
or the product found at the base of the distillation column. This situation requires the implementation of a monovariable control system, as sketched in Figure 5.

Figure 5  The monovariable control system providing the quality check of the distillation product

B. Selection of the commands used in the quality control process of the products

From the system control’s point of view, the distillation process is a multivariable system (Multi-Input-Multi-Output). In the case of the distillation process there is a range of possible pairs of commands, which could lead to various and possibly, unexpected interactions, and, therefore, a good selection of the pairs of commands is compulsory.

1) Relative Gain Array. Among the various methods of analysis and design of the multivariable control structures, the Relative Gain Array (RGA) proved to be a good and efficient candidate. The relative gain array was introduced by Bristol in order to solve the stationary regime interactions between the control commands and the output variable of the process [11]. The relative gain between the output $Y_i$ and the command $U_j$ is defined as:

$$\lambda_{ij} = \left. \frac{\partial y_i}{\partial u_j} \right|_{u},$$

in which $u$ are the control agents and $y$ the controlled variables.

In the case of distillation columns that can be characterized as a 2x2 multivariable systems, such as the case of a propane-propylene distillation column, the desired pairs of commands that are needed for the propane concentration control in the distilled mixture $X_D$, as well as in the product found at the base of the column $X_B$, are presented in Table I.

<table>
<thead>
<tr>
<th>Pair of commands</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflux - Vapors</td>
<td>L-V</td>
</tr>
<tr>
<td>Reflux - Base</td>
<td>L-B</td>
</tr>
<tr>
<td>Distilled - Vapors</td>
<td>D-V</td>
</tr>
</tbody>
</table>

2) MAR calculus using Unisim Design software. In order to successfully use equation (3), one needs to compute the denominator (changes in concentration) and the numerator (changes in the commands). The changes/variations of concentration can be computed by the UniSim design simulator. Therefore, in the following paragraphs, we will present a series of necessary stages that are needed to configure the simulator for the computation of the relative gain of the L-B control structure. The relative gain is calculated using the following relationship:

$$\lambda_{11} = \frac{\Delta X_D}{\Delta L_{B\text{-act}}},$$

In the following, we present the undertaken computational steps for obtaining the relative gain array for a propylene-propane distillation column, whose parameters are described in Table II.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of theoretical plates</td>
<td>-</td>
<td>133</td>
</tr>
<tr>
<td>Theoretical input/feeder plate</td>
<td>-</td>
<td>99</td>
</tr>
<tr>
<td>Pressure at the top</td>
<td>bar</td>
<td>9</td>
</tr>
<tr>
<td>Pressure at the base</td>
<td>bar</td>
<td>10</td>
</tr>
<tr>
<td>Temperature at the top</td>
<td>ºC</td>
<td>18.8</td>
</tr>
<tr>
<td>Temperature at the base</td>
<td>ºC</td>
<td>33.3</td>
</tr>
<tr>
<td>Reflux flow</td>
<td>kg/h</td>
<td>300000</td>
</tr>
<tr>
<td>Flow at the base</td>
<td>kg/h</td>
<td>7309</td>
</tr>
<tr>
<td>Distilled flow</td>
<td>kg/h</td>
<td>19350</td>
</tr>
<tr>
<td>Input flow</td>
<td>kg/h</td>
<td>26889</td>
</tr>
<tr>
<td>Input temperature</td>
<td>ºC</td>
<td>27.3</td>
</tr>
<tr>
<td>Input pressure</td>
<td>bar</td>
<td>10.4</td>
</tr>
</tbody>
</table>

The following steps are required in order to obtain the denominator of equation (4):

a) In the configuration window of the mathematical model, and under the Design tab, select the Specs option in order to verify that the specifications for the reflux flow and product base flow are active. The normal values are 300000 kg/h for the reflux flow, and 7300 kg/h, for the product base flow.

b) In order to compute the first value of the propane concentration inside the distilled, one should run the simulation software, and under the
The propane concentration inside the distilled before changing the reflux flow is recorded: \( x_D = 0.997752 \) molar fractions.

c) In the configuration window of the mathematical model of the distillation column, and under the Design tab, select the Specs option in order to verify that the specifications for the reflux flow and for the product base flow are active. Select Reflux Rate and increase its value with 1%, from 300000 kg/h to 303000 kg/h. The product base flow value is kept constant, at a value of 7300 kg/h.

d) The next step is to run the simulation software and, under the Worksheet tab, select Composition. The propane concentration inside the distilled after changing the reflux flow is subsequently recorded: \( x_D = 0.997847 \) molar fractions.

e) The above simulated values of the distilled concentration are used to calculate the following ratio:

\[
\Delta x_D \bigg|_{B=ct} = \frac{0.997847 - 0.997752}{303000 - 300000} = \frac{0.000096}{3000} = 3.2 \cdot 10^{-8} \text{ fr. mol. kg}^{-1} \text{h}^{-1}.
\]

The complete calculation of eq. (4) denominator request for a clear definition of the specific conditions for which the propane concentration inside the base product, \( x_B \), is constant. The following steps are required:

f) In the configuration window of the distillation column, under the Design tab, select the Specs option and then select Reflux Rate to modify its value to the previously used value of 300000 kg/h.

g) Subsequently, select Btms Prod Rate that corresponds to the product base flow rate, and check the Active option.

h) In order to introduce the propane concentration in the product base, click on Add and select Column Component Fraction option, to finally click on Add Spec(s)... button.

i) From within the resulted configuration window set the following parameters: Stage: Reboiler (considered to be the last plate of the column); Spec Value: 0.075; Components: Propane.

j) Check the Active option from within the configuration window.

k) Select Reflux Rate option and increase its value with 1%, from a value of 300000 kg/h to 303000 kg/h.

l) Run the simulation software and under the Worksheet tab, select Composition.

m) The propane concentration inside the distilled after changing the reflux flow rate is recorded: \( x_D = 0.99785 \) molar fractions.

n) The following ratio is calculated:

\[
\Delta x_D \bigg|_{x_B=ct} = \frac{0.997850 - 0.997748}{303000 - 300000} = \frac{0.000102}{3000} = 3.4 \cdot 10^{-8} \text{ fr. mol. kg}^{-1} \text{h}^{-1}.
\]

Having calculated both numerator and denominator of equation (4), we could, therefore, obtain the relative gain for the propylene-propane distillation column:

\[
\lambda_{L-B} = \frac{\Delta x_D}{\Delta L} \bigg|_{B=ct} = \frac{3.2 \cdot 10^{-8}}{3.4 \cdot 10^{-8}} = 0.941.
\]

Using the above computational technique, we calculate the relative gain for the L-V and D-V structures, as shown in Table III.

### TABLE III. RELATIVE GAIN VALUES

<table>
<thead>
<tr>
<th>Pair of commands</th>
<th>L-B</th>
<th>L-V</th>
<th>D-V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.941</td>
<td>14</td>
<td>0.026</td>
<td></td>
</tr>
</tbody>
</table>

The results shown in Table III reveal the fact that the L-B control structure used for product quality check is the most suitable for the particular case of the chosen distillation column, and therefore, it is normally recommended that this structure to be developed and implemented at an industrial scale. We should note, however, that in dealing with control systems that are associated to distillation columns with heat pumps, one must also take into account the most important dynamic component, namely, the gas compressor.

### IV. CONTROL STRUCTURES ASSOCIATED TO THE GAS COMPRESSOR

From a system control point of view, the centrifugal compressors used within the heat pumps can be characterized by the existence of two control structures: a control structure for the compressor’s frequency and a anti-surge structure. Figure 6 presents the schematics of such control structure [12].

The study of the centrifugal compressors has revealed that complex dependencies between the compressor’s load, the change in the compressor’s discharge-suction differential pressure, and the surge limit can currently occur [13].
Fig. 6 Schematics of a standard control structure of a centrifugal compressor

Figure 7 shows the occurrence of such tight dependencies among the above mentioned variables.

Fig. 7 Compressor statically characteristics and surge limit

Given the fact that there isn’t a single value for the surge limit, the authors consider that this situation gives rise to a twofold solution regarding the automated anti-surge system. The first solution takes into consideration the automated system presented in Figure 6, which prescription, for full range operational capabilities, should have the maximum value presented in Figure 7. The automated anti-surge system is useful for all the cases in which the net load of the compressor is relatively low. If the compressor’s load is, on the contrary, high, the automated system must be re-correlated to take into account other compressor variables, in order to decrease the net load, the power consumption, and therefore, to enhance its efficiency. A possible solution to the above mentioned issues is based on correcting the vapor flux rate that is measured in the control loop of the compressor’s total load, as shown in Fig. 8. This structure is better suited to correct for the desired behavior by using the correlation between the anti-surge limit and the other compressor variables, as presented in Figure 7. We should note that this is not the only possible structure, and literature research shows that there are also other variants of the anti-surge control structure [12].

V. PRESSURE CONTROL

Distillation columns are structures that have to be operated at constant pressure. To achieve this goal, pressure control systems have been installed to work with the classical distillation columns [14]. According to the literature, such control structures can be classified in the following categories:

a) Total condensation columns:
   − Systems based on changing the cooling agent’s flow rate;
   − Systems based on changing the heat transfer area;

b) Partial condensation columns:
   − Systems based on the removal of the non-condensing gases by using their internal pressure as an energy source;
   − Systems based on the induced/external aspiration of the non-condensing gases (ejectors, compressors etc).

The propylene-propane distillation column is a total condensation column that uses pressure control systems that are based on the change of the heat transfer area.

In the case of distillation columns with a pump heat, the pressure control structures are totally different. The lack of the condenser, whose role was to insert the pressure control agent, shifts the automated system focus towards the heat pump’s compressor or towards the reflux container of the column. Regulating the pressure control of a distillation column by using a gas compressor, subjects it to a mode of operation that relies heavily on variable loads and frequencies, which could both influence in the long run the correct mechanical behavior of the device. The second solution is based on the ideas of operating the compressor at a constant frequency and of modifying the input rate flux that enters the reflux container. Figure 9 presents a schematic diagram of such pressure control structure.

The compressed vapors that exit the compressor are separated into two fluxes: one that is used as a heat exchange agent at the column’s reboiler, and one that is responsible for mass and energy conservation processes within the column. However, we should point out that the system sketched in Figure 9 is not
optimal, as the column pressure builds up as the combined result of both compressor’s action and the reboiler’s thermal load. As a result, the temperature of the output vapor flux from the second heat exchanger cannot be in principle controlled, and therefore, the pressure inside the reflux container cannot be adequately controlled.

Another possible variant of a pressure control system is shown in Figure 10. The novelty in the model is represented by the fact that a part of the vapor flux that was previously compressed inside the compressor is recirculated and redirected towards the compressor’s intake. In this case, we observe that the output gas flux pressure is greater than the intake pressure (the pressure at the top of the column), which makes this structure more suitable for all the cases in which the column pressure is not sufficiently high enough.

Validating the choice for the most suitable structure to be use for distillation columns with pump heat can only be achieved by using numerical simulation.

**CONCLUSIONS**

The system control design for distillation columns with pump heat should combine the requirements of product quality check processes with the ones characteristics to the column compressor. There is, however, a significant interaction between the two components, namely the distillation column and pump heat, within the column’s reboiler, an interaction that cannot be neglected and which should be taken into account.