Optimization of the vacuum system of a resin plant

Ana Rita Tiago Inácio
anaritainacio@tecnico.ulisboa.pt

Instituto Superior Técnico, Lisbon, Portugal

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Abstract

This work was realized under an internship developed in Euroresinas – Indústrias Químicas, in Sines, between October 2017 and March 2018, aiming to seek possible process improvements on the production of resins plant, by optimizing the vacuum system and consequently increasing the profitability of the process.

The study consists in two parts. First, it was necessary to know the amount of water vapor and air that the vacuum system extract from the ureic reactors. For that, it was used reactor and condenser modelling, based on mass balances and enthalpic balances. To get the volume of air to be extracted to the reactor, it was necessary to develop three models. During the phase with the most adverse operating conditions, *i.e.*, when requires 0,2 bar of pressure, the volume was 27,4 m^3.

In the second part, it was studied the use of a vacuum central to replace the actual vacuum system of the resins plant. In this study, the vacuum central was designed and was obtained a volume of 35,3 m^3, therefore a height of 5,65 m and a diameter of 2,82 m.

Further, was concluded with the design of the vacuum, that affecting vacuum central, that the piping connecting the central to the vacuum pumps has a diameter that does not allow full use of the pumping speed of the pumps. As this is the diameter currently used in the plant, it was concluded that is necessary to change this diameter so as not to cause as much resistance to the passage of sucked air.

Finally, it was obtained a reduction of electricity consumption that the vacuum central implementation could give, which was, about, 64 %. At the end of a year, this reflects a saving of about € 20 000.

Keywords: Vacuum; Vacuum Design; Modeling; Resin Production Process; Industrial Case.

1. Introduction

EuroResinas is a company that produces formaldehyde based resins, and synthetic formaldehyde resins are a group of chemicals with very intensive use. These can be found in multiple current applications, like in the products derived from wood and paper, where the resins assure the function of binding agents.

According to [1] the bonding agent or adhesive is defined as the material having adherent properties, *i.e.*, a material which has the ability to hold other materials together on its surfaces, forming a strong and lasting surface bond.

The wide range of resins employed in the wood industry, the three most important types of thermoset resins are aminoresins, phenolic resins and isocyanates. Among the aminoresins are urea-formaldehyde resins (UF), melamine-formaldehyde resins (MF) and melamine-urea-formaldehyde resins (MUF) [1].

The production of UF resins is performed in two steps. In the first step, the urea will react with formaldehyde through its amine groups, which may form mono-, di- and trimethylol ureas. The second step consists in condensing the methylol ureas to form polymers of some molecular weight. This basic procedure for the formation of UF resins can be manipulated in various ways, with the aim of obtaining a resin with the best possible properties in terms of adhesion, reactivity and coverage.

Vacuum technology is widely used in many chemical applications, since it is used for the purpose of performing basic thermal and mechanical operations to process reaction products under conditions that preserve them [2].

This project was made for the company EuroResinas - Indústrias Químicas, S.A., and that company belongs to the Sonae Arauco group, dedicated to the manufacture and commercialization of synthetic resin based formaldehyde. Thus, in the plant are produced four families of resins: ureic resins, melamine resins, copolymerized resins and phenolic resins.

This work has, as the main objective, increase the profitability of the resins plant through the optimization of the vacuum system of the ureic and melaminic reactors, and consequently of the minimization of the energy consumption affecting this system. Since an analysis made a priori to the energy consumptions of the resins plant, it was verified that one of the great consumers of energy is the reactors vacuum system.

Considering also the economic weight of the product - formaldehyde based synthetic resins - and the permanent need to reduce production costs, there is a need to improve process technology.

1.1 Urea-Formaldehyde Resins (UF) and Melamine-Urea-Formaldehyde Resins (MUF)

UF resins are the most important group of adhesives used in the particleboard industry, and the most relevant resins in the aminoresin group [3]. They are the most produced resins worldwide and therefore represent 80% of total aminoresins [4]. The remaining 20% corresponds mainly to MUF resins, a small percentage being destined to the resins synthesized from other aldehydes and/or other amino compounds [5]. The annual production of UF resins is approximately five million tonnes [3], and about 70% of this production is used in the wood industry for several purposes.

Regarding MF resins, these have a much higher water and moisture resistance than UF resins and can be used in a wide range of wood products, such as wood panels for outdoor use, and sheltered exteriors, as well as in paper laminates of high and low-pressure [5]. However, melamine is five times more expensive than urea, which causes high inflation in the final price of MF resin. For this reason, MF resins have now become more accessible by introducing urea together with melamine to give UF resins melamine-fortified when the melamine content is less than 5 %, or MUF when the percentage of melamine is greater than 5% [6].

1.2 Vacuum Systems

The vacuum generation in a closed system consists essentially in the removal of atoms/molecules of gas (air, for example) from within that system. Different degrees of vacuum can be obtained, depending on the amount of air being removed from inside a chamber. However, a vacuum chamber that is empty, *i.e.*, that is free of all matter, is called the perfect or absolute vacuum. What can never get [7] [8] [9].

Vacuum systems are currently an essential part of numerous scientific and industrial projects, used in the most varied applications, which extend to practically every engineering areas.

Vacuum systems have as its main components a chamber, vacuum pumps and pipes, Figure 1.1. Like this is a system that is part of many processes in the industry, it is important that its components are well designed, in order to get the evolution of the desired pressure for each particular case.

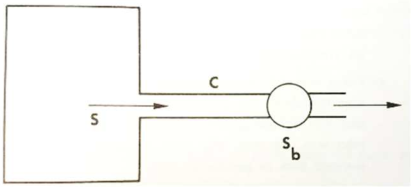

Figure 1.1 Chamber, tube and pump, S is the effective pumping speed, C is the conductance and S_b is the pump speed [10].

The design of a vacuum unit is not only determined by the performance data of the various process equipment, but also by the vacuum operating range [9]. In the high vacuum range, individual equipment sizes are not as important for the overall installation dimensions as the required suction capacity, and size and dimensions of the vacuum pumps. Generally, in the vacuum process engineering in chemical industry, the vacuum units consist of following major components [11]:

i. Vacuum equipment for the execution of the process;
ii. Condensation equipment for the steam compression;
iii. Vacuum pumps or combination pumps;
iv. Accessories, such as separators, heat exchangers, vacuum vessels and measuring and control instruments.

The exact calculation of the conductance of a given system is usually a complicated procedure, so the equation (1.1) defining it. This equation was formulated under molecular flow conditions and for a simple geometry type, like a tube, that is most often found.

$$U(Short\ tube) = 12{,}1D^3\left(\frac{1}{L+4\frac{D}{3}}\right) \qquad (1.1)$$

$$L/s\ for\ air\ at\ 20^oC$$

Until now, any type of reduction of the effective speed of a pump in the chamber has been ignored. That reduction may be caused by connections between the pump and the chamber. Equation (1.2) demonstrates this difference between speeds.

$$S_{eff} = \frac{SU}{S+U} = \frac{S}{1+S/U} = \frac{U}{1+U/S} \qquad (1.2)$$

To calculate the time required to produce the vacuum at a given pressure was used equation (1.3).

$$t = 2{,}303\frac{V}{S}\log_{10}\frac{p_0}{p} \qquad (1.3)$$

2. Vacuum system implemented in the production of resins

During the production of a resin batch, two vacuum levels are required: small vacuum and vacuum [10]. The small vacuum is used for most of the production time of a resin reference and its main objective is to maintain the internal pressure of the reactor, with the set point being used of 0,99 bar. The vacuum has a fundamental function, cooling the resin as well as its dehydration, and has as set point 0,2 bar.

The steam is drawn from the reactor and then sent to the shell and tube condenser. Cooling water flows through the tubes (the tube side) and steam flows outside the tubes but inside the shell (the shell side). The condensate returns to the reactor.

On the other hand, gases that do not condense are directed to the distillates vessel and then directed to the vacuum line. Every two reactors share a vacuum pump, Figure 2.1.

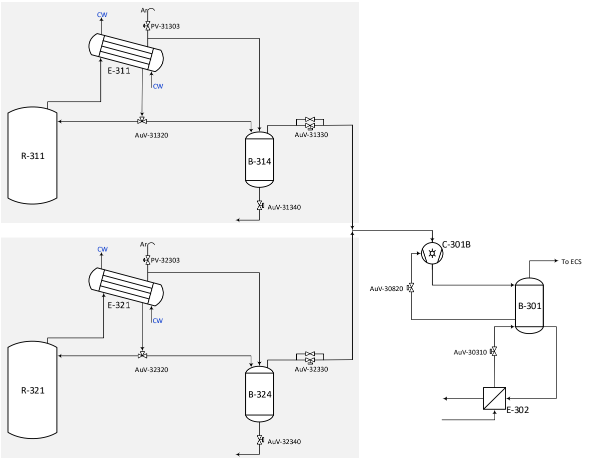

Figure 2.1 Simplified vacuum system diagram of R-311 and R-321 reactors.

2.1 Mass Balance and Energy Balance

The main purpose of these mass and energy balances was to determine the amount of air to be withdrawn to the reactor. However, during the analysis of the balance sheets, other important conclusions were drawn during the work. Thus, the systems presented in Figure 2.3 and Figure 2.4 were the basis for constructing of both mass and energy balances, giving the source to models that try to describe as best as possible the reality of the system.

By the analysis of Figure 2.4, it is possible to observe numerous phases that occur during the production of a resin batch. In short, at the beginning of production, the small vacuum is connected. After the condensation step of the resin, which the viscosity value of the mixture is regularly checked, another soda filler is added, and the cooling step is initiated, where the vacuum of 0,2 bar is initiated. After this step, the instruction to restart the small vacuum is given.

2.1.1 Simplified Model

In this model, an approximation was made to the reactor, the stirring is perfect. It was considered that the system represented the following situation: tank with reaction mixture with exclusive cooling of the cooling water coils, which are inserted into the reactor. This model was based on a resin reference that is made only in a small vacuum.

The reference state used was 20ºC, working pressure and liquid state for all components. The balance equations are the equations (2.1), (2.2) and (2.3).

$$\frac{\Delta(\Delta H)}{dt} = -Q_{ret} \tag{2.1}$$

$$M_L \bar{C}_p^L (T - T_{ref}) \tag{2.2}$$

$$M_{CW} \bar{C}_p^{CW} (T_{out} - T_{in}) \tag{2.3}$$

The numerical resolution of this differential equation, using the Euler Method, is expedient and represents the temperature variation of the reactor as a function of time, as shown in Figure 2.2. This figure was obtained using solver to get the specific heat of the resin.

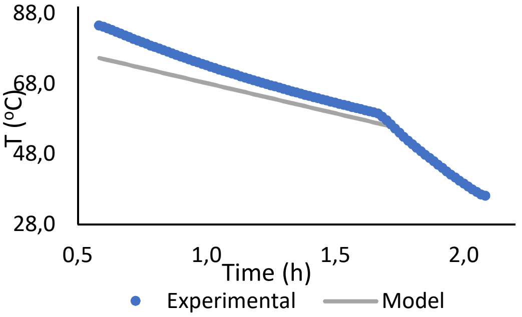

Figure 2.2 Representation of the simplified model with recalculated Cp.

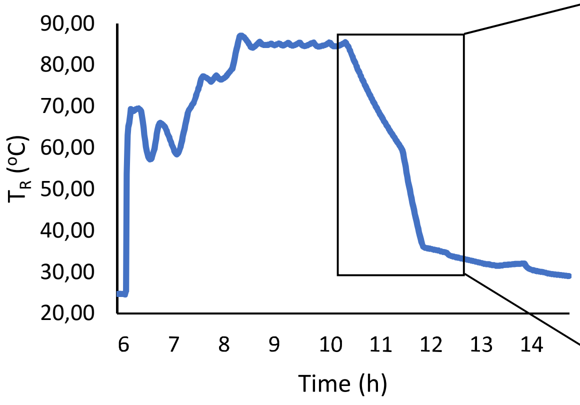

Figure 2.3 Evolution of the reactor temperature as a function of time during the production of a resin batch.

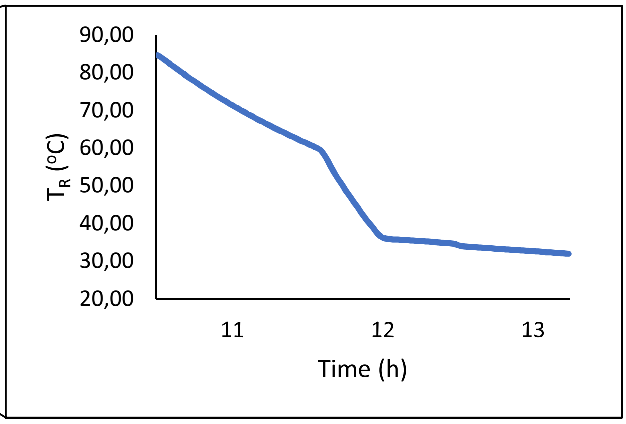

Figure 2.4 Cooling step under 0,2 bar vacuum.

2.1.2 Intermediate Model

In this model, some approaches were also made:

i. Inside the reactor, perfect agitation was admitted;
ii. In the condenser, total condensation was admitted;
iii. In the reactor, it was admitted that only air and water vapor are drawn.

It was considered that the system represented the following situation: tank attested with reaction mixture with cooling of the cooling water coils, which are inserted into the reactor, steam outlet, and condensed water inlet. This model was analyzed as a resin reference having a vacuum of 0,2 bar during cooling.

The reference state used was 20ºC, working pressure and liquid state for all components. The balance equations are the equations (2.4), (2.5), (2.6), (2.7) and (2.8).

$$\Delta H_L = \Delta H_V + Q_{ret} + \frac{\Delta(\Delta H)}{dt} \tag{2.4}$$

$$\Delta H_L = M_L \bar{C}_p^L \left(T_L - T_{ref}\right) \tag{2.5}$$

$$\Delta H_V = M_V \bar{C}_p^V \left(T_V - T_{ref}\right) + M_V \Delta H_{vap}^V \tag{2.6}$$

$$Q_{ret} = M_{CW} \bar{C}_p^{CW} (T_{in} - T_{out}) \tag{2.7}$$

$$Q_{ret} = \Delta H_V - \Delta H_L \tag{2.8}$$

With all values calculated and using the Euler Method, the intermediate model was obtained, which was compared with the experimental results, Figure 2.5.

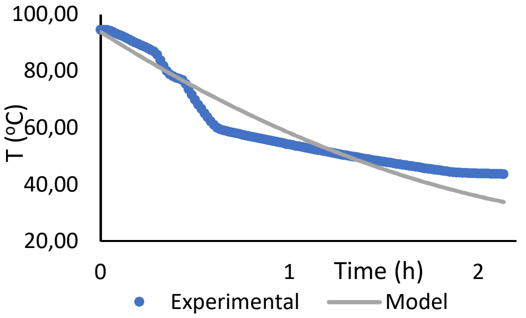

Figure 2.5 Representation of the intermediate model.

2.1.3 Final Model

The mass balance in this situation is more complete since it considers two components extracted by the vacuum system: water vapor and air. Therefore, it is assumed that the vacuum system draws saturated air. Equations (2.9), (2.10), (2.11) and (2.12) represent the mass balance.

$$\ln P_V = A - \frac{B}{T - C} \tag{2.9}$$

$$k = \frac{P_V}{P} \tag{2.10}$$

$$y_{água} = k x_{água} \tag{2.11}$$

$$M_L = M_V + \frac{dM}{dt} \tag{2.12}$$

With all values calculated and using the Euler Method, the intermediate model was obtained, which was compared with the experimental results, Figure 2.6.

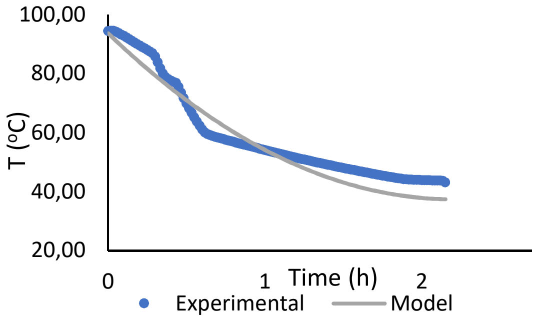

Figure 2.6 Representation of the final model.

Through this model, it was possible to get the values of the amount of water vapor and air extracted from the reactor in the small vacuum phase and in the vacuum phase. The summary of these values is represented in Table 2.1.

Table 2.1 Volumes of water and air removed by the vacuum system.

Step	**Volume (m^3)**	
	Water	**Air**
***Small* Vácuo – Biginning**	2,78E-3	5,19E+1
Vácuo	1,83E-2	2,74E+1
***Small* Vácuo – End**	9,95E-4	4,98E+1

3. Vacuum Central Analysis

As the main purpose of optimizing the vacuum system affecting the ureic reactors of the Resins Plant, it was proposed the study of a vacuum central.

3.1 Central Design

The premises allowed to perform this design were:

i. The distillates chamber is filled with water up to one-third of its volume, thus remaining two-thirds of its capacity;

ii. The condenser on the side of the tubes is filled with water vapor and condensed water up to two-thirds of its volume, thus being a third of its capacity;

iii. The situation considered was the vacuum phase, which in terms of design is the worst-case scenario, where it is necessary to keep the reactor at a pressure of 0,2 bar and, therefore, to draw more steam of water and air from the same in a shorter time gap.

The total volume, 35,33 m^3, was obtained using a factor of 1,1 since it was the approximation found to account for the volume of all connections between the different equipment.

In terms of design, the vacuum central was treated as a tank, so it was admitted at the beginning of the calculations that it had a ratio between height and diameter of 2. After this, equations (3.1) and (3.2) were used to determine the dimensions of the central.

$$V = \frac{\pi D^2}{4} \times H \tag{3.1}$$

$$D = \sqrt[3]{\frac{4V}{x\pi}}\ (6.45) \tag{3.2}$$

Consequently, the parameters resulting from the design of the vacuum central, height and diameter, were obtained. These parameters are shown in Table 3.1.

Table 3.1 Design parameters of the vacuum central.

Height (m)	5,65
Diameter (m)	2,82

3.2 Vacuum Design

It was considered the vacuum phase, which in terms of sizing is the worst-case scenario. Since it is necessary to maintain the reactor at a pressure of 0,2 bar and therefore to draw more steam of water and air from it, within a shorter time.

It was considered that the connection piping of the vacuum central and the pumps would be 1 meter in length, *i.e.*, their positioning inside the plant would be immediately above the pumps.

The conductance of the system was determined, and for this, we used equation (1.1). The use of this equation implied that what circulates inside the pipes is air at 20ºC.

The manual of the liquid ring pumps [12], in the plant unit, was used to get the pumping speed as a function of the pressure - 0,2 bar.

It has been found that the difference between the pumping rate, S, and the effective pumping speed, S_{eff}, is very large. The evaluation of the fraction of pumping velocity that is being used by the system was expressed in Table 3.2.

Table 3.2 Parameters for design the vacuum associated with the control panel.

Design Parameters	
U (L/s)	55,98
S (L/s)	216,67
S_{eff} (L/s)	44,49
Effective use of S (%)	20,53
t (min)	21,2

To discuss these results, we used a sensitivity analysis. That is, for different pipe diameter values all other parameters have been recalculated. The pumps used would always be those currently in the plant, so the value of pumping speed is constant. The value of the diameter was varied because it has the greatest influence on the final value of the conductance. Since the narrower the tube through which the air is forced, the greater its resistance to passage. The values obtained for this sensitivity analysis are presented in Table 3.3.

Table 3.3 Sensitivity analysis of vacuum design parameters.

Design Parameters	Sensitivity analysis		
	$D = 13\ cm$	$D = 18\ cm$	$D = 98\ cm$
U (L/s)	226,57	569,09	49371,78
S (L/s)	216,67	216,67	216,67
S_{eff} (L/s)	110,75	156,92	215,72
Effective use of S (%)	51,12	72,43	99,56
t (min)	8,5	6,0	4,4

The last case considered in the sensitivity analysis, where the diameter is 98 cm, would not be a case to consider in practice. Since the diameter is almost equal to the length of the tube. It is only one case that demonstrates the theory of vacuum design.

3.3 Central Vacuum Model

With three liquid ring pumps available, the main purpose of the model for the operation of the vacuum central was to create a mode of action for each pump, as needed at present, of the four ureic reactors. For this reason, five possible scenarios were designed to simulate these same operative needs. The scenarios were as follows:

i. Scenario 1 - Real scenario: a scenario was drawn based on the planning for the month of October 2017.

ii. Scenario 2 - Worst scenario: it was a scenario assuming that all the reactors needed a vacuum at the same time and during the hour and a half complete, that is, the worst situation one can have.

iii. Scenario 3 - Intermediate Scenario 1: It was a scenario assuming that all reactors needed a vacuum at the same time for only one hour, that is, a less aggressive scenario than the previous scenario.

iv. Scenario 4 - Intermediate Scenario 2: It was a scenario assuming that all reactors needed a vacuum at the same time for only half an hour, that is, a scenario even less aggressive than the worst case scenario.

v. Scenario 5 - Best scenario: it was a scenario, that none of the reactors needed a vacuum at the same time as any of the other reactors, *i.e.* it is the most favorable situation one could have.

3.3.1 Scenario 1 - Real scenario

After the description of the scenario, the desired operating principle for this model, which is the phase start / stop of the three vacuum pumps, has been put into practice to eliminate the needs of each reactor. As shown by the Figure 3.1.

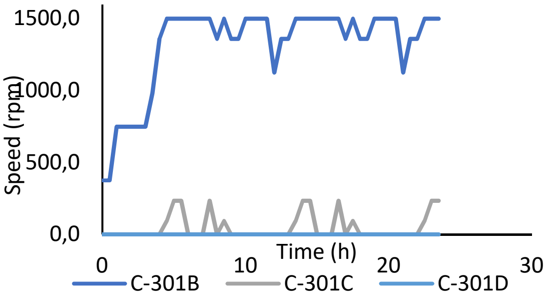

Figure 3.1 Representation of the central model for the real scenario.

3.3.2 Scenario 2 - Worst scenario

The worst scenario was drawn admitting the worst-case scenario that could happen in a resin production planning, *i.e.*, that all four reactors have the same vacuum needs simultaneously. This scenario is represented by the Figure 3.2.

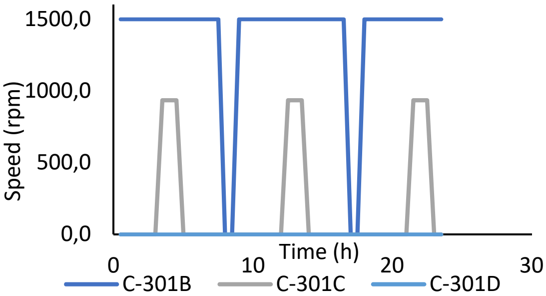

Figure 3.2 Representation of the central model for the worst scenario.

3.3.3 Scenario 3 - Intermediate Scenario 1

The intermediate scenario 1 was drawn presumed improvement in the conditions in the worst scenario, *i.e.* instead of the total overlap of the four reactors in the vacuum phase, they only need vacuum, at the same time, for 1 hour. They are out of time for half an hour. This scenario is represented by the Figure 3.3.

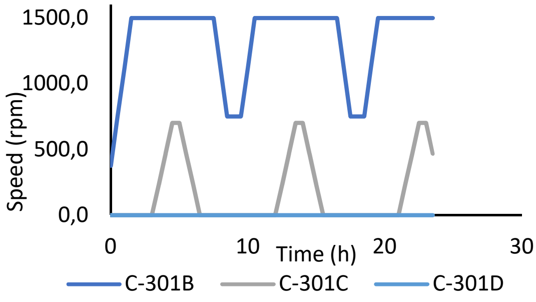

Figure 3.3 Representation of the central model for the intermediate scenario 1.

3.3.4 Scenario 4 - Intermediate Scenario 2

The intermediate scenario 2 was plotted admitting another assumed improvement in the worst scenario, *i.e.*, instead of the total overlap of the four reactors in the vacuum phase, they only have this need for half an hour. They are out of time for an hour. This scenario is represented by the Figure 3.4.

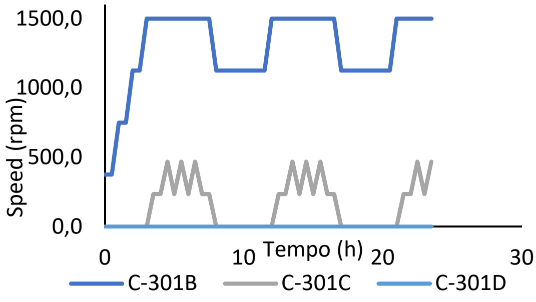

Figure 3.4 Representation of the central model for the intermediate scenario 2.

3.3.5 Scenario 5 - Best Scenario

The best scenario was drawn admitting the best case that could happen in a resin production planning, that is, that all four reactors never have the same vacuum needs simultaneously. This scenario is represented by the Figure 3.5.

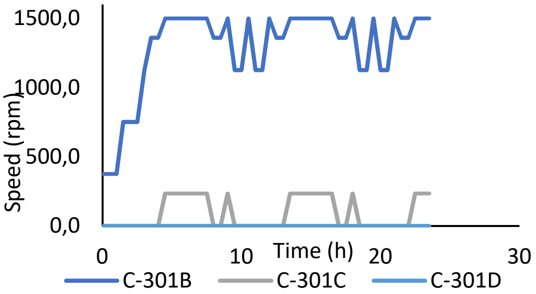

Figure 3.5 Representation of the central model for the best scenario.

3.4 Layout and Control Suggestion for Vacuum Central

Continuation study of the vacuum central also involved the execution of a proposal of layout and control for the new installation.

Therefore, resorted to the use of a PLC (Programmable Logic Controller). Because this is the type of control most used, in case of discontinuous processes.

In this specific case, the vacuum requirements of each of the reactors are communicated to the PLC through an electric signal through a pressure transmitter, located in the reactor. The pressure value inside the vacuum central unit is also transmitted to the PLC. With all this information collected, the PLC makes vacuum pumps work. These same vacuum pumps are equipped with a variable speed drive, that is, a frequency converter that controls the speed of the pump motor. This control of the pumps implements the desired operating principle for the model of the vacuum central. This consists of starting and/or stopping the three vacuum pumps according to the requirements of the four reactors.

4. Conclusions

Among the three models created, although the last two have a better fit, none of them accurately describes reality, which is to be expected. Because, for the creation of these models, temperatures were read by an infrared thermometer, and in this reading are associated errors, namely: wear of the instrument itself, the error of reading of the observer, air currents inside the plant, among others. Nevertheless, and since this is a case of a practical nature, the quantities obtained were quite valid.

In the study of the vacuum plant, a very important fact was reached, for the pipe diameter currently used in the vacuum system, the percentage of use of the pumping speed of each pump is manifestly lower than would be desired. Since the sensitivity analysis carried out, it was sufficient to increase the diameter of the piping connecting the pump to the system by 10 cm (*i.e.*, from 8 cm to 18 cm) so that the percentage of use of the pumping speed would increase from 20,53 % to 72,43%. This would already be sufficient to reduce the energy consumption by the vacuum system, since the pumps, working at a lower speed, would be able to suppress the needs of the reactors.

With the explanation of five possible scenarios, in the scaling of the resins among the four reactors, it can be concluded that the vacuum central would be able to realize the different levels of vacuum that the resin production requires, using only two pumps, always leaving stop the backup pump.

Finally, with the determination of the expected return with the implementation of the vacuum central, it can be concluded that this alternative is feasible. Because it presents, on average, a reduction in consumption of 64% between the current situation and the future one. Hence, this translates into a saving, at the end of a year, of approximately 20 thousand euros.

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