ISSN: 2834-4928

Research Article

Journal of Electrical Electronics Engineering

Energy Optimization Study In an Ethanol Production Unit Using Pinch Technology

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Submitted: 2023, May 17; **Accepted:** 2023, Jun 02; **Published:** 2023, Jun 23

Citation: Siqueira Magalhães, S. R. D., Neves, Y. P. C. D., Santana Silva, O. D. A. D. (2023). Energy Optimization Study In an Ethanol Production Unit Using Pinch Technology. *J Electrical Electron Eng, 2*(2), 187-195.

Abstract

This work presents an energy optimization study in a distillation and dehydration unit of a conventional ethanol producing bio refinery, based on the Pinch method. This proposal resulted in savings of 69.2% in operational costs with utilities, just with energy integration, turning the process significantly cheaper.

Keywords: Energy Integration, Pinch Analysis, Ethanol.

1. Introduction

With large global demand for supplies, the industry in general has been increasingly looking for energy solutions that result in savings and sustainability. This is because energy consumption is by far the largest source of expenditure in the vast majority of industrial plants on the planet, and in some of them, there is no reliable energy integration, leading to more expenditure and more pollution from the burning of fuels to attend the specificity of the processes, often making the operation unfavorable to competitive markets.

An industrial complex nowadays can easily have an energy demand similar to the consumption of some small and medium size cities. This is due to the high energy consumption that is necessary in some processes, such as the production of ethanol in bio refineries, a product that has been used as an alternative fuel in many countries, including Brazil, as a solution to reduce atmospheric pollution, but due to the distillation stages needed in the process, production becomes very expensive and as a consequence, it loses space for fossil fuels in the market, but Ethanol is necessary in the fight against global warming, making clear the importance of reducing expenses for its production, making the process more competitive in the global scenario.

Throughout the design of an industrial plant, engineers face two different problems, one being the dimensioning of unitary operations individually, an approach widely studied in the graduation of chemical engineering, and the second is the process of integration of unitary operations, which is still little widespread, but addresses the whole process as an efficient unit, such a study began with the dissemination of the idea of energy integration, after the crisis of the 70s [1].

There are two categories of energy integration methods available today, those formulated in mathematical programming and those derived from heuristic-thermodynamic techniques. The methods that use mathematical programming present a significant complexity, even more so if there are a large number of streams in the process. However, heuristic techniques, such as pinch analysis, even though imprecise from a mathematical point of view, are effective, taking into consideration their simplicity, and manage to generate plausible results with regards to the economy [2].

Therefore, it is clear that a well-integrated energy network in an industrial plant can make all the difference in the cost of the process and consequently, makes the operation much more competitive in the eyes of the world market. However, to design a well-integrated energy plant, it is necessary to use some tools; one of them is the "pinch" technology, fundamental in the elaboration of an energy integration study in a cheap, simple and very effective way.

2. Related Work

2.1 Ethanol

Due to the growing discussion about global warming caused by the large amount of polluting gases released into the atmosphere in the last decades, the change in the world energy matrix to a cleaner, renewable and sustainable one has proven necessary. With it, new fuels, techniques and technologies were developed aiming at high yields and low costs, but always seeking sustainability. Currently, the two main renewable fuels produced in the world are bioethanol and biodiesel, each with its own techniques and feedstock [3].

According to the last balance sheet of the Renewable Fuel Association (RFA), from 2014 to 2019 Brazil was responsible for

30% of the ethanol production in the world, table 1, occupying the second position among the producing countries, behind only the United States, which produced 54%.

Regiion	2014	2015	2016	2017	2018	2019	World Production (%)
USA	14.313	14.807	15.413	15.936	16.061	15.800	54%
Brazil	6.760	7.200	6.760	6.860	7.920	8.620	30%
EU	1.445	1.387	1.377	1.400	1.430	1.440	5%
China	635	813	845	860	1.050	900	3%
Canada	510	436	436	470	480	500	2%
Índia	85	195	275	210	400	530	2%
Tailând	310	334	322	370	390	420	1%
Argentina	160	211	264	290	290	290	1%
Rest of world	865	391	490	414	549	600	2%
Total	25.083	25.774	26.182	26.810	28.570	29.100	

Source – RFA, 2020.

Table 1: Ethanol production in the world from 2014 to 2019 in million US gallons.
Source - RFA, 2020

Ethanol not only has great potential as a fuel, but it can also be applied in several sectors such as pharmaceutical, food, industrial, among others. From it, for example, acetaldehyde, acetic acid, ethyl acetate, ethylene and a variety of chemical products are produced, including polymers [4]. Thus, the use of Ethanol as a feedstock in the production of different chemical products, normally produced from petroleum derivatives, appears as an increasingly attractive alternative, mainly because it is a sustainable technology, following the trend of green engineering [5].

In the Brazilian industry, the production of ethanol is mostly carried out through the use of sugarcane as feedstock, given that such cultivars are historically important in the country. In the current processes, a large part of the bagasse is burned to produce thermal and electrical energy in cogeneration systems. However, in the production of ethanol, an alternative to the use of sugarcane juice is the use of these lignocellulose materials in 2nd generation bio refining through pre-treatment and hydrolysis processes to transform them into fermentable sugars from carbohydrates, cellulose and hemicellulose [6,7]

In a conventional Brazilian bio refinery, after the receiving and cleaning of the sugar cane, the operations are divided into Extraction of sugars present in the sugarcane juice; recovery and concentration of sucrose; fermentation, biochemical process that produces alcohol through the metabolism of microorganisms; distillation and dehydration, which compose the separation systems [8]. The block diagram shown in figure 1 can understand the process in a bio refinery.

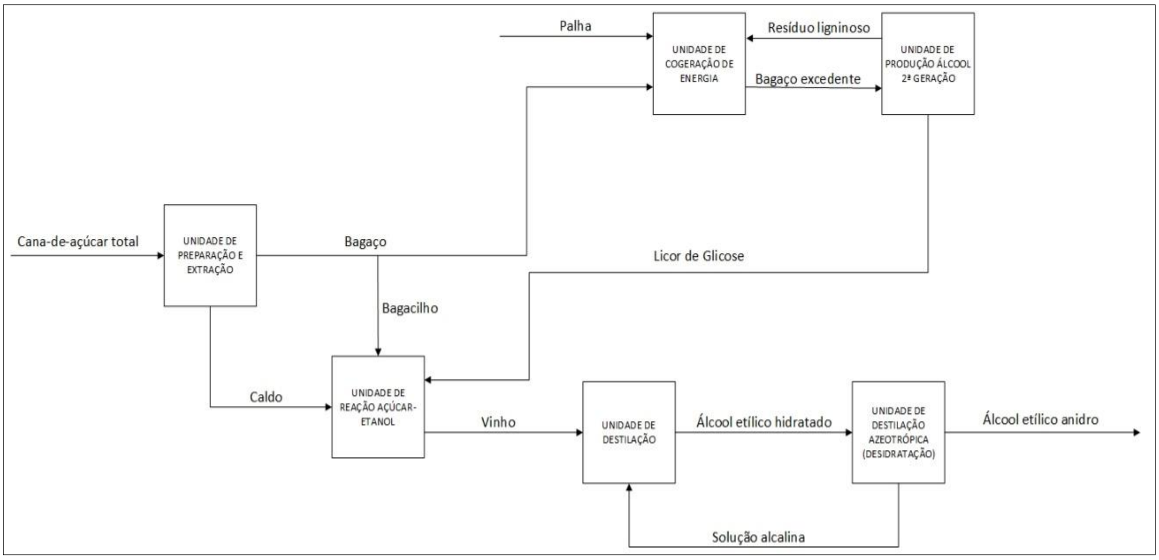

Figure 1: System of a 2nd generation ethanol bio refinery
Source – Adapted from DIAS, 2001.

2.1.1. Distillation e Dehydration

As explains, the wine that leaves the fermentation unit is then headed for the distillation stage, where there is the recovery of ethanol through distillation in multiple stages that separate alcohol from water based on physical-chemical properties [9]. The target product of this unit is hydrated ethanol with a content of 92.6 and 93.8% of ethanol in mass.

In Brazil, the configuration normally used in distillation units is composed by 5 columns: A, called the wine exhaustion column; A1, the wine epuration column; D, second generation alcohol concentration, in it the most volatile components of the mixture are removed from the top in order not to contaminate the AEHC, such columns complete the so-called distillation set. Next, we have the columns B, called rectification column and B1, exhaustion, closing the set known as rectification, where the Hydrated Ethanol is obtained.

To acquire the product as an additive in gasoline, the Hydrated Ethanol must be dehydrated to obtain an alcohol content of at least 99.3% by mass. In Brazil, one of the main methods of dehydration used in the alcohol industry is the extractive distillation by using the mono ethylene glycol solvent, known as MEG.

Figure 2 shows the process flow diagram (PFD) of a distillation and dehydration unit without energy integration.

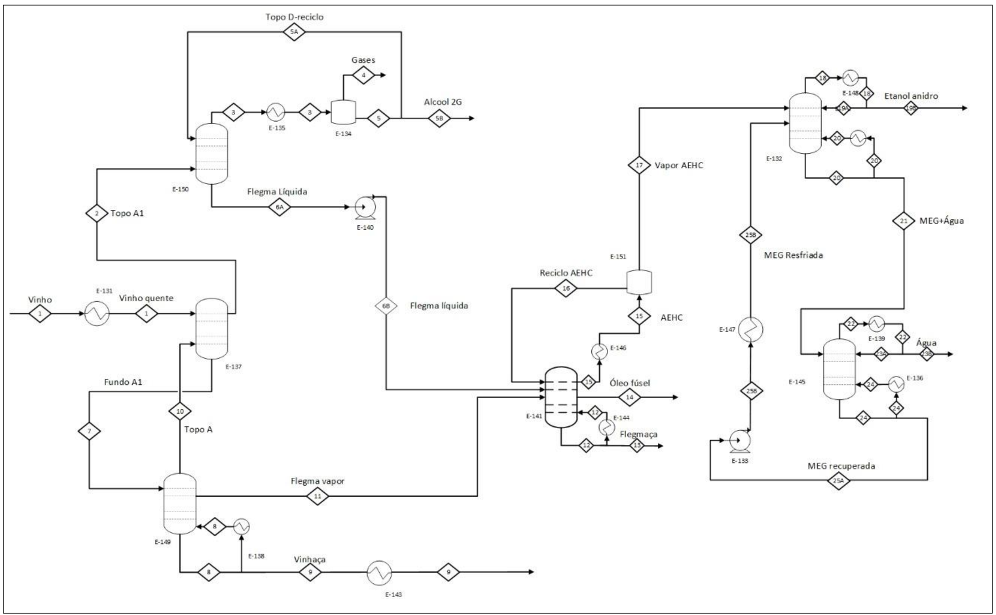

Figure 2: Process flow diagram (PFD) of a distillation and dehydration unit without energy integration

Source -Author

2.2 Pinch Analysis

The heuristic method, known as pinch analysis, derived from the studies of presents a methodology that is based on a range of techniques already established for the application of the first and second law of thermodynamics, providing a better understanding of the interaction between the thermal utilities and the process in question and aiming at an improvement in the configuration of the heat exchanger network in order to obtain an energy optimization [10,11]. In the literature, pinch technology can often be found in existing plant energy retrofitting work with regard to integration based on the technology in question.

According to the pinch analysis is divided into two well-established stages, the first being the determination of the benchmarks that establishes the minimum energy consumption in the process and the second consists of the synthesis of the heat exchanger network that meets the targets obtained in the first stage [12].

2.2.1. Benchmark Goals

Benchmarks or "super targeting", as it is called in pinch technology, are defined as the minimum consumption of utilities in the process, as well as the smallest possible number of thermal exchange units and the smallest global thermal transfer area related to a minimum delta temperature between hot and cold process currents, called ΔTmin [13]. There are some tools to determine the benchmarks of the process, one of them widely used, is a graphic method known as composite curves.

This tool is no more than a graphical representation of the energy balance of a process, that is, the temperature profile versus enthalpy, designed from the compilation of all the currents in one, forming the hot composite curves obtained from the sum of the thermal loads for cooling and the cold composite curves, derived from the sum of the thermal loads for heating.

By dissecting the composite curve diagram it is possible to see that the vertical region of the graph, represented in figure 3, indicates the possibility of energy recovery between the currents, while the region in which the curves approach each other horizontally, indicates how much the heat exchange is possible, so that the closer the curves are horizontally, the greater the perspective of heat exchange until the position where this distance reaches its lowest value in relation to the vertical axis (T). In this point one finds ΔTmin (minimum temperature difference), indicating that the remaining energy required completing the energy balance must come from the system of units [14].

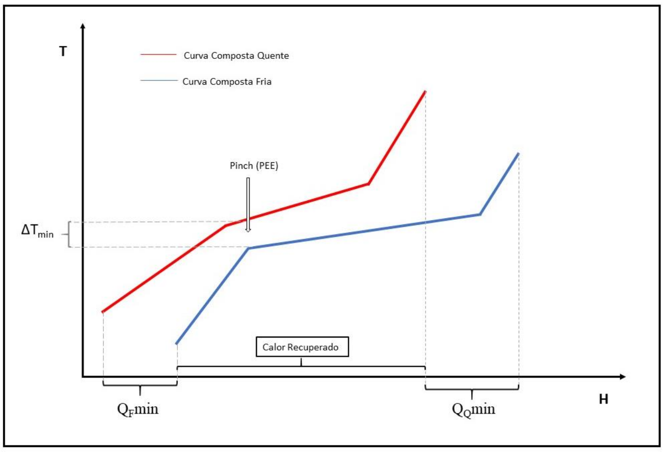

Figure 3: Composite curve diagram
Source – Author

Once the composite curve diagram is plotted, you can then analyze the results for a given ΔTmin. In it is found the pinch (or energy bottleneck, PEE) by using temperatures values for the hot and cold pinch. In addition, the plot shows the values of minimum energy consumption for hot utility (as in steam) and cold utility (as in cooling water), as seen in figure 3. Such information comprises what reference targets for a given ΔTmin define.

The pinch method is not restricted to presenting utility consumption targets in a process; it can also allow the synthesis of the heat exchanger network by means of its own methodology with the objective of achieving the benchmarks.

2.2.2. Heat Exchanger Network

The synthesis of heat exchangers, as previously exposed, composes the second stage of energy integration and aims to build a network of heat exchange in order to achieve the benchmarks determined in the first stage, following a series of rules established by the "pinch" technology proposed by [15]. Thus, there are two fundamental rules, the first of them (number of streams rule) says that the number of cold currents just above the pinch should be lower or equal to the number of cold currents, if this premise is not met, the cold currents should be split, however, if the number of cold streams just below the pinch is not lower or equal to the number of hot streams, the latter should be split. The second is the heat capacity rule (MCp) and determines that for combined currents just above the pinch, the MCp of the hot current must be smaller or equal to that of the cold stream, while just below the pinch, the MCp of the cold stream must be smaller than that of the hot stream.

For the representation of the heat exchanger network, proposed the grid diagram or "Grid Structure", represented in figure 4, as an easy way to visualize the division of the two regions, the pinch point and the exchanger allocation [16,17]. However, as presented above, the rules of the number of chains and MCp should be followed.

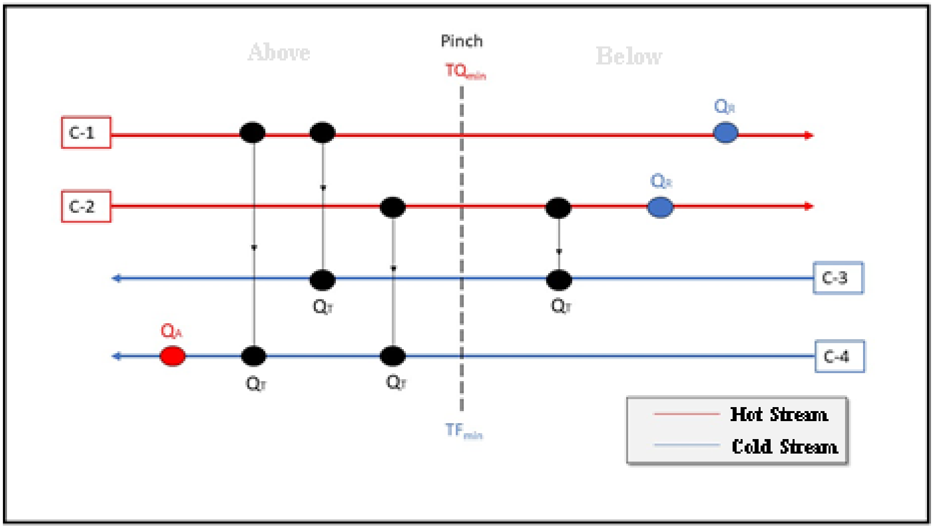

Figure 4: Grid Diagram of a Network of Heat Exchangers
Source – Author

3. Methodology

Based on the literature and following the steps set by pinch technology, we developed the following methodology flowchart for the present paper, illustrated in figure 5.

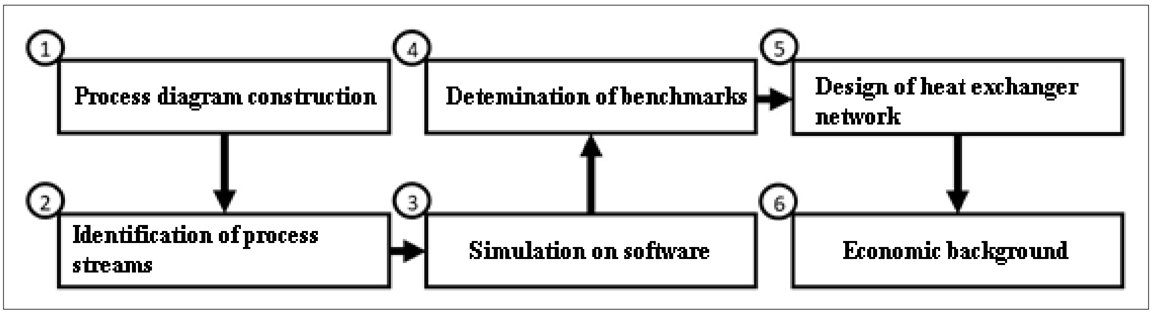

Figure 5: Methodology Flowchart
Source – Author

Process Diagram Construction

Identifying processes involved in ethanol production in the distillation and dehydration stages of a conventional bio refinery, as well as the unit operations, detailed in a process flow diagram (PFD), containing all the currents of the production line.

Identification of the Streams That Require Heat Exchange in the Process

From the PFD, listing the lines that need heating and/or cooling within the process, from the location of the heat exchangers located in them, cataloging the inlet and outlet temperatures of these utilities. In addition, the mass flows, pressures and compositions in each current must be identified for the following step.

Simulation of the Process in Software

Through process simulation software such as Aspen Plus V8.8®, find the input and output enthalpies of each current. To do this, we use the catalogued data from the previous step, in the construction of the simulation.

Determination of the Benchmarks by the Pinch Method

Once the enthalpy values and temperatures of the process currents are known calculate the average heat capacities and determine the reference targets by constructing the composite curve graph (Enthalpy X Temperature). Afterwards, the energy bottleneck must be identified and consequently ΔTmin, which will serve as the basis for the synthesis of the heat exchanger network, by the pinch method rules.

Synthesis of Heat Exchanger Network by Pinch Method

By knowing the temperature variations and the MCp of each stream requiring thermal exchange, it becomes possible to construct the grid diagram, respecting the pinch method rules, based on the referential goals found in the previous step.

Economic Background

Comparing the economic results obtained by applying the proposed energy integration with those of a common ethanol plant without optimization, proving the financial gain of such an application.

4. Outlook and Discussions

With the identification of the currents in need of thermal exchange, through the process flowchart of a distillation and dehydration unit in a conventional bio refinery, presented in figure 2, it was possible to elaborate the temperature diagram presented in figure 6, in which it demonstrates the differences of temperatures in the identified process currents.

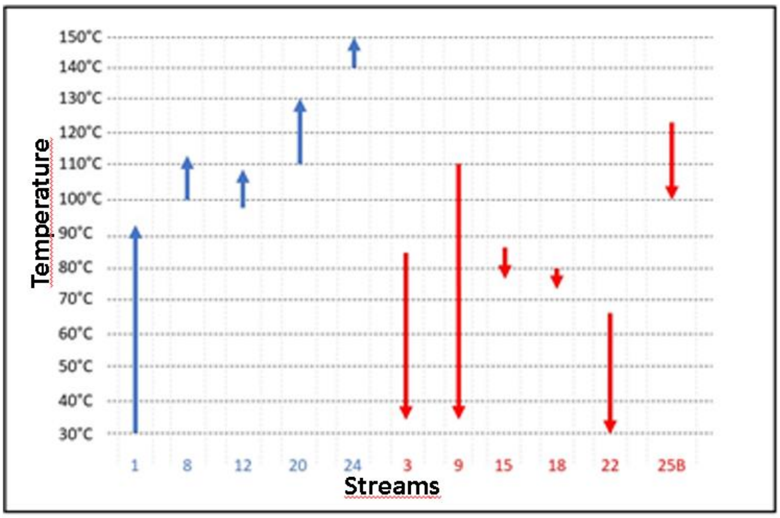

Figure 6: Temperature Difference of Process Currents
Source - Author

The remaining data required for the simulation of the process in software for further application of the pinch technology steps were extracted from the literature [18]. The pressures and flows of each selected stream are shown in table 1.

STREAMS	DESCRIPTION	Pressure (kPa)	Flow (ton/hr)
1	WINE LOAD	138	207
3	TOP OF COLUMN D	133,8	0,2
8	BOTTOM OF COLUMN A	152,5	70,1
9	VINASSE LOAD	152,5	105,1
12	BOTTOM OF COLUMN B	135,7	14,7
15	TOP OF COLUMN B	116	16,1
18	TOP OF EXTRACTIVE COLUMN	101,3	15,1
20	BOTTOM OF EXTRACTIVE COLUMN	101,3	11,0
22	TOP OF RECOVERY COLUMN	50	1,1
24	BOTTOM OF RECOVERY COLUMN	50	10,0
25B	MEG RECYCLE	101,3	10,0

Table 2: Streams Properties
Source – Author

In addition to the data shown in table 1, the compositions of all major components (water, ethanol, glycerol, isoamyl alcohol, and glucose and monoethylene glycol) were based on the simulation presented by with such information, it was possible to perform the process simulation through Aspen Plus V8.8®, obtaining the values of the enthalpies in each stream that required thermal exchange, allowing the calculation of the MCp following the equation (1).

$$\Delta H = M.\,Cp.\,\Delta T \tag{1}$$

As ΔH, the variation of enthalpy, M, the mass flow, Cp, the Heat Capacity and ΔT, the variation of temperature.

The calculation of the average calorific capacity, which is configured by the product of the flow with the calorific capacity, is obtained from the ratio of ΔH by ΔT, as observed in equation 1. The values of ΔH and average calorific capacity (MCp) of each stream are shown in table 2, as well as their thermal classifications, split between hot and cold currents.

STREAM	TYPE	DESCRIPTION	Ti (°C)	Tf (°C)	ΔH (kW)	MCp (kW/°C)
1	COLD	WINE LOAD	30	93	15560	247
3	HOT	TOP OF COLUMN D	85	35	11,299	0,23
8	COLD	BOTTOM OF COLUMN A	100	112	70	6
9	HOT	VINASSE LOAD	110	35	13620	182
12	COLD	BOTTOM OF COLUMN B	98	108	2329	233
15	HOT	TOP OF COLUMN B	85	78	4287	612
18	HOT	TOP OF EXTRACTIVE COLUMN	80	75	3640	728
20	COLD	BOTTOM OF EXTRACTIVE COLUMN	110	130	168	8,4
22	HOT	TOP OF RECOVERY COLUMN	65	30	43	1,23
24	COLD	BOTTOM OF RECOVERY COLUMN	140	150	78	7,81
25B	HOT	MEG RECYCLE	125	100	184	7,35

Table 3: Stream Data for the Process Flow Diagram
Source – Author

Using the calculated MCp values it was possible to build the composite curve plot following the determination of the benchmarks. The Aspen Energy Analyser V8.8® software was used for this and the composite curve plot is shown in figure 7 and demonstrates that energy integration in this process is possible because the heat can be recovered.

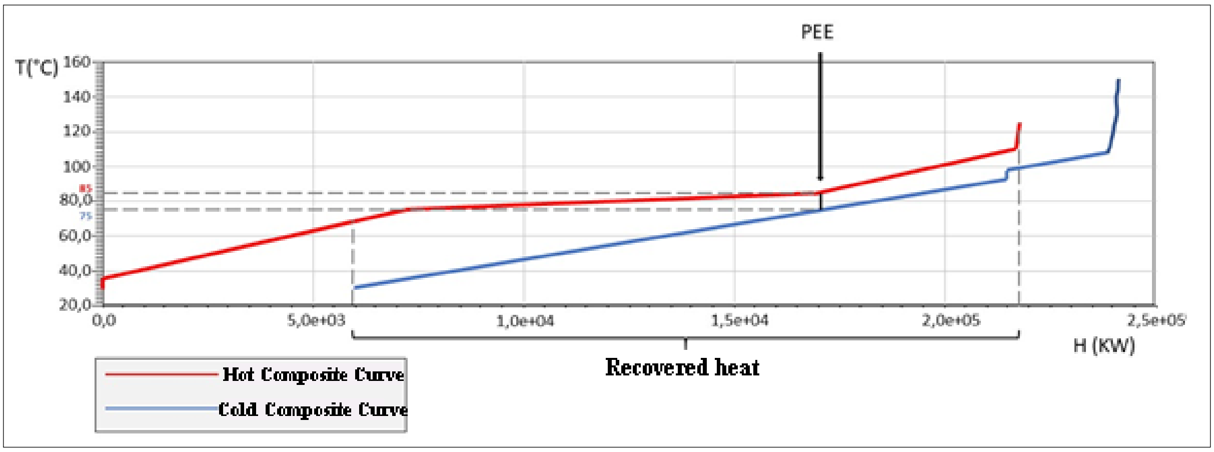

Figure 7: Composite Curves Chart
Source -Author.

With the composite curve plot created, it became possible to identify the pinch point (or energy bottleneck, PEE) which stood at 75°C for cold streams and 85°C for hot streams, giving a ΔTmin with the value of 10°C. With the benchmarks set, the next step was to construct the grid diagram to make it possible to synthesize the network of heat exchangers for the process [19].

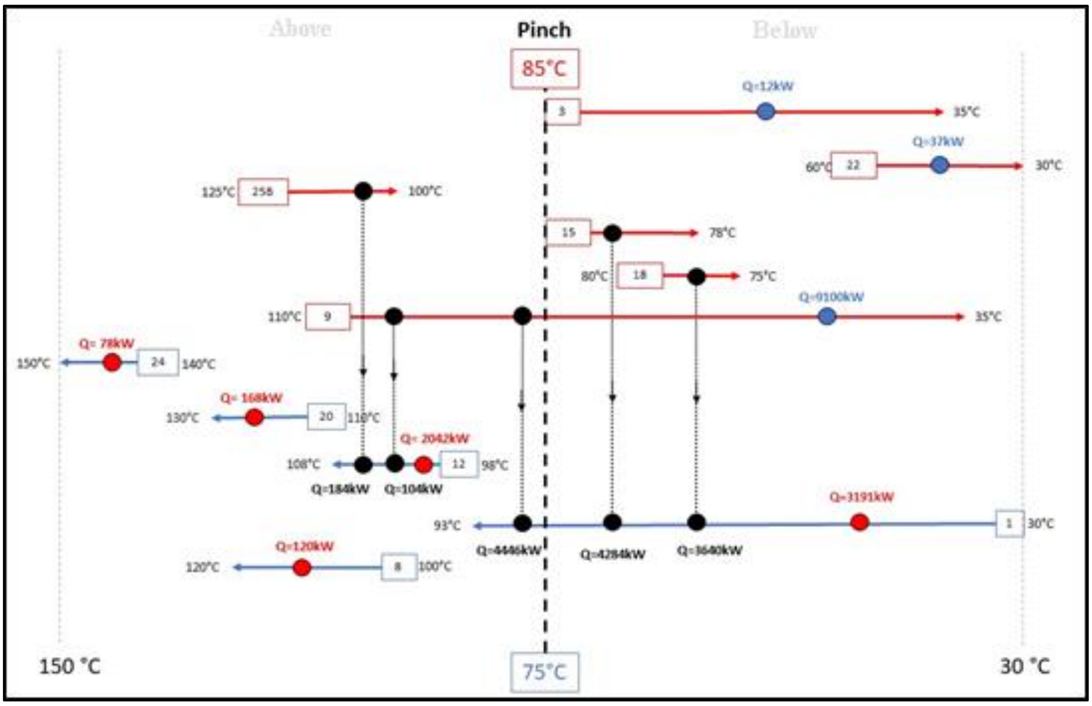

Figure 8: Grid diagram for the process
Source - Author

On the figure 8, the grid diagram is presented and exposes the values of heat transferred from the hot to the cold streams, where there was the energy integration, represented by the connections between the pairs of knots, as well as the amount of heat to be added or removed by external heating and cooling utilities, represented by the red and blue knots, respectively, in order to maintain the specificities of the process currents. From the grid diagram presented in figure 8, it was then possible to design the heat exchanger network (RTC) representation, shown in figure 9, for better viewing.

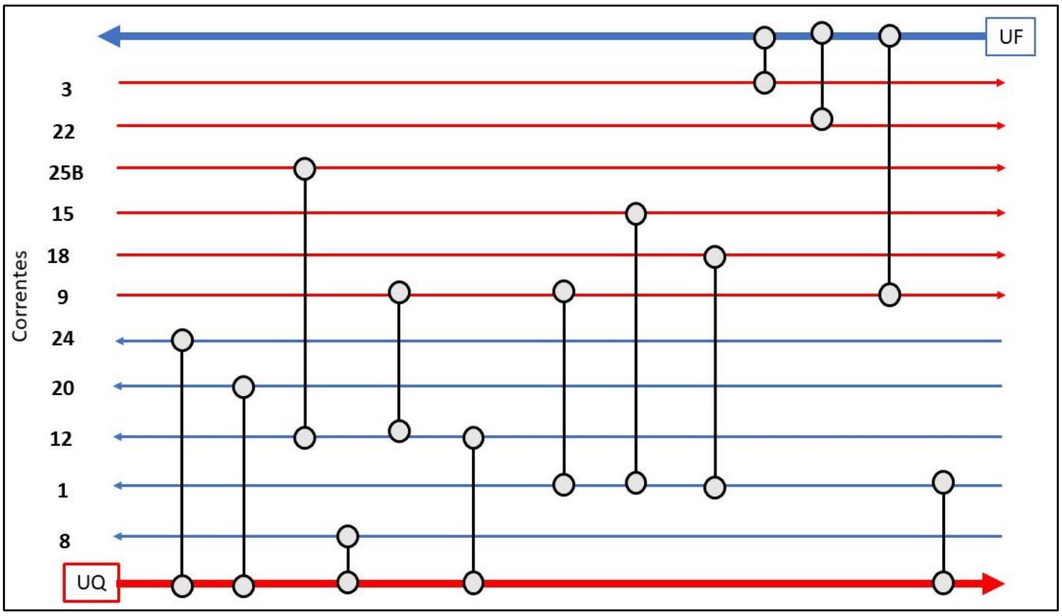

Figure 9: Heat Exchanger Network
Source - Author

Based on the grid diagram of figure 8 and the following representation of the Heat Exchanger Network shown in figure 9, we can say that it is possible to integrate the streams 1, 9, 12, 15, 18 and 25B so that the specificities of the process are maintained.

Therefore, with all the stages of pinch technology proposed by Linnhof and collaborators, completed, it was possible to build a network of heat exchangers that integrate the process streams, energetically. Based on the PFD shown in figure 2, a new process flow diagram was developed, this time with the energy integration lines represented in the ethanol distillation and dehydration process. Figure 10 presents the proposal for energy integration in the process involved.

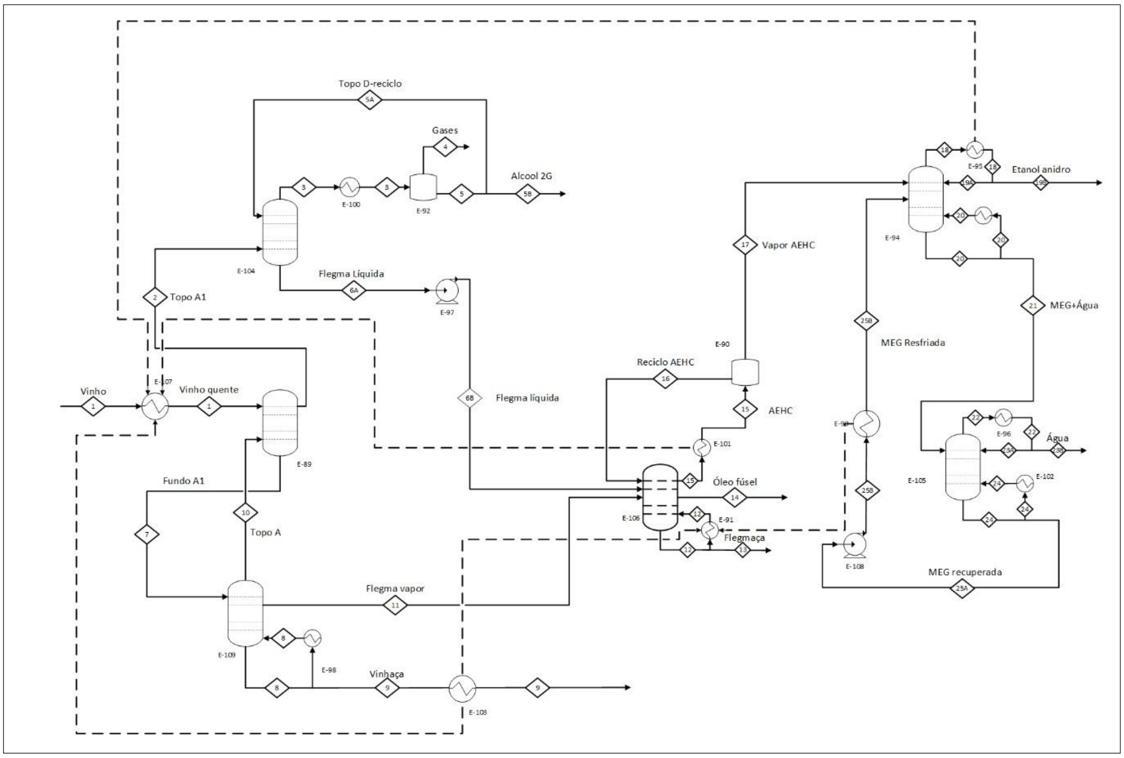

Figure 10: Process flow diagram (PFD) of a distillation and dehydration unit with energy integration
Source - Author

Based on the results obtained, it was then possible to calculate in financial terms, the savings achieved by applying energy optimization. For this, it was taken into considered that the inlet and outlet cooling water (AGR) design temperatures are 30°C and 45°C respectively, and for the steam received in the unit the inlet temperature is 184°C to 50 Psi.

For such financial estimate, it was considered that the cost of the m^3 of cooling water is 0, 10 R$ and that for the steam (50 Psi) is 90 R$/ton.

Utilities	**Cooling Water**		**Steam (50 Psi)**	
	Before integration	**After integration**	**Before integration**	**After integration**
Enthalpy (kW)	21.782,61	9.155	18.257	5.599,00
Flow	1.248,65 m^3/hr	524,79 m^3/hr	160.793,43 kg/hr	49.311,63 kg/hr
Cost (R$/mês)	89.902,4	37.785,0	10.419.414,2	3.195.393,6

Table 4: Financial Reduction of Utilities in the Process

Thus, the data in table 4 shows that the operational costs had a reduction of 69.2% with the energy optimization in comparison to the total expenses with hot and cold utilities of a conventional distillation and dehydration unit, without the integration. This makes ethanol production significantly cheaper and consequently more competitive.

5. Conclusion

Through pinch analysis, the proposal of energy integration in a conventional ethanol distillation and dehydration unit could be successfully developed. Applying the benchmarking steps, it was proven that energy optimization in the process in question was possible. Thus, the synthesis of the heat exchanger network, proposed by pinch technology, was also completed; featuring an energy integrated system and 69.2% more cost-effective, making the process considerably cheaper and feasible.

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