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Energy analysis and process simulation for the energy efficiency improvement of existing chemical plants

Vyacheslav Dyudnev[a], Vitalii Korotkii[a], Stanislav Novgorodtsev[a], Stanislav Boldyryev[b], Alessandro Di Pretoro[c], Julia Bragina[a], Marina Trusova[b], Flavio Manenti[c,*]

[a] SIBUR, Tobolsk, Tyumen Oblast, Russia, 626150
[b] Tomsk Polytechnic University, 30 Lenin Ave, Tomsk, Tomsk Oblast, Russia, 634050
[c] Pol itecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", 32 Piazza L. Da Vinci, Milan, Italy, 20133
flavio.manenti@polimi.it

In recent years, energy efficiency has been one of the topics of major concern from a worldwide perspective as clearly stated by the International Energy Agency (IEA,2021). The energy waste reduction not only improves the process performances from an economic perspective but reduces as well the equivalent CO_2 emissions. This research work is the product of a collaboration between the SIBUR petrochemical company and the Tomsk and Milan Polytechnic Universities during the Process Operations Management program aiming at the training of the personnel and at the troubleshooting practical problems of the petrochemical industry. SIBUR is a petrochemical company with a unique business model focused on the integrated operation of two main segments, namely fuel and raw materials and petrochemistry. Inefficient use and big losses of steam/condensate, obsolete equipment are the main reasons for the development of energy efficient strategies. Different sites need identification of real technical problems and process drawbacks by application of novel approaches and local methods. This work deals then with the analysis of light hydrocarbon unit with the purpose of reducing energy consumption and solving operational problems. Structuring and analysis of information on the consumption and distribution of steam and condensate at the operated unit were performed. Main drawbacks were detected and technical measures for a more efficient redistribution/involvement of steam in production processes were proposed. Process simulation of light hydrocarbon unit with the related utility streams and equipment was performed via Aspen HYSYS. Revamping of existing heat exchanger network and application of extra units for better heat recovery and most efficient utility use were proposed according to established energy optimization methodologies. The results were then validated by a detailed design of the additional heat exchangers and consequent simulation of the optimized process scheme. As a result, the formation of secondary boiling steam in tanks and associated losses into the environment was reduced by 100 %; the electricity consumption for chillers was decreased by 20%; steam consumption was cut by 64% on the heater; debottlenecking allows to increase the yield of current units and improve plant efficiency; reduction of inefficient use of steam at steam header by 71%. The equipment design and the updated economic assessment were performed as well and resulted in substantial savings for the company. Moreover, according with established indicators, an additional environmental analysis was carried out and showed relevant CO_2 emissions reduction corresponding to the methane not used for combustion thanks to the energy recovery.
In conclusion, the detailed energy analysis and process simulation of the existing plants allowed not only for a considerably higher profitability of the process in general but also for a higher sustainability in agreement with the world guidelines concerning the environmental impact of the industry.

1. Introduction

During the last decades, energy efficiency has gained substantial interest both due to economic and environmental concerns (IEA, 2021). In particular, the United Nations have set more and more constraining sustainability goals over the next decades with the purpose to reduce specific emissions and lead the perspective of the future process industry towards a greener approach.

Several chemical plants currently working were not designed according to the best practice in terms of energy use. On the one hand, this lack of attention during the design phase was due to the fact that a major part of these plants were built decades before the knowledge and the technologies aimed at a better use of energy were not yet available. On the other hand, the concerns related to the environmental issues have been only recently stressed by the industrial and political communities in the light of the climate changes and pollution issues deriving from an excessive impact of the petrochemical industry.

For these reasons, the detection and the analysis of possible measures aimed at the improvement of existing plant is not of minor importance with respect to the conception of innovative methodologies concerning the optimal design of plants ex novo (Masa et al., 2017).

Effective strategies for plants revamping usually implies new investments such as the case of pinch analysis. This methodology developed during the last decades of the 20th century allows indeed to improve the heat recovery between process streams reducing the external duty demand at the price of additional heat exchangers. The benefits of this heat integration between different units can be stressed even more in case not only the single plant section but the entire plant is taken into account when calculating all the possible hot and cold streams matches. Moreover, high-pressure duties exploited in certain units could be further cooled down if coupled with other processes optimizing the amount of generated steam. The price to pay for a bigger control volume is obviously a much higher computational effort.

This research work addresses then the need of a performance enhancement for an existing gas processing plant located in Siberia by exploiting detailed process simulations and plantwide pinch analysis for the demand side management. The different plant sites will be all taken into account with the main purpose to improve the performances of the less effective one.

Before introducing the technical details about the research work carried out, it is worth highlighting that this study is born from a collaboration between academic and industrial sectors. To be more precise, the Russian petrochemical company SIBUR decided to invest in order to improve the productivity and the performances in general of its site in Tomsk. In particular, it detected some area of interest ranging from non-conventional unit operations to energy efficiency.

In order to provide technical consultancy aimed at finding the optimal solution to these problems, without impacting too much on the already existing plant layout, The Polytechnic University of Tomsk and the SuPER Centre of Politecnico di Milano set up the "Process Operations Management" course. This research work is then the results of one of the research areas handled during this course and, in particular, is the one related to the energy efficiency domain.

2. The SIBUR LPG site case study

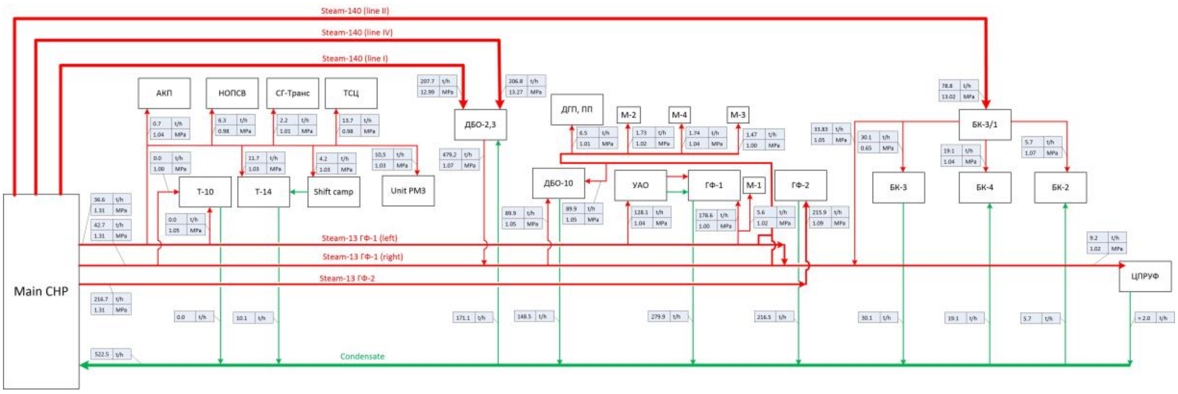

Figure 1: Condensate and steam pipes layout (SIBUR Tobolsk)

The plant whose performances should be optimized is the SIBUR LPG site located in Tobolsk. To be more precise, in this research work we are dealing with the utility side of the plant.

As it can be noticed in block diagram in Figure 1, where red and blue lines represent the steam and condensate pipelines respectively while the white boxes are the process units grouped according to the four subsections,

there is only one steam generator system that feeds all the unit needing a hot duty. In particular, thick red lines represent high pressure steam (13 MPa) while narrow red lines represent medium pressure steam (1.3 Mpa).
After being used, the HP steam at the outlet of the two main blocks is then sent to a MP steam collector and further used by other units. However, in the original configuration, this duty consumption occurs in sequence and no crossing streams matches are present. This layout suggests that there is room for improvement by means of a proper energy analysis and with a deeper pipeline network understanding in order to consider possible integration between different plant sections as well. Moreover, since the steam generating system works in a closed loop configuration, makeup water should be only provided in order to compensate the evaporation losses. This means that the heat recovery maximization could be not only a considerable advantage in terms of heat duty requirement, but it can also reduce the amount of low enthalpic content steam to vent to the atmosphere thanks to a better condensation.
Therefore, in the next section, further details about the methodologies used to optimize the plant utility management both in terms of energy and costs are presented in detail before showing the obtained results.
It is worth remarking that, an obtained investment aimed at improving the energy effectiveness of the plant is considered profitable by the SIBUR Company if the corresponding Internal Rate of Return (IRR) is about the 25 % or higher.

3. Energy analysis and process simulation

The very first step towards the LPG section analysis and optimization was the generation of its digital twin on a process simulator. Among the commercial simulators Aspen HYSIS was selected for this purpose.
After that a pinch analysis was performed according to the methodology discussed by Di Pretoro and Manenti (2020a, 2020b) by accounting for all the utility and process hot and cold streams of the plant, not only for the LPG section. This allowed to identify the enthalpic level of each stream and to detect all those cases in which the available energy was not effectively exploited.
The energy savings were then used to evaluate the reduction in terms of CO_2 equivalent emissions by means of the correlations proposed by Gadalla et al. (2006). In the same reference, the authors prove that the energy consumption in oil and gas processing plants are the main item contributing to the Global Warming Potential (GWP) while the equivalent emissions related to the equipment production can be neglected. For this reason, it is reasonable to expect that the most effective improvements will be the consequence of a better heat recovery and a more proper steam use.
In order to quantify and compare the obtained possible solutions, the energy analysis has been coupled with a preliminary economic assessment. The cost of the new units as well as the operating expenses related to the energy consumption have been estimate by means of the Guthrie (1969,1974) – Ulrich (1987) – Navarrete (2001).
It is worth remarking that the final goal of this study is not to perform all the modifications that are theoretically possible in order to obtain the optimal configuration. The optimal solutions of a pinch analysis usually imply too substantial changes and, even when coupled with a preliminary economic assessment, might neglect some operational or other kind of inconveniences such as maintenance, land consumption, pressure drops due to the presence of many more pipes and units, etc. On the one hand, some of those issues cannot even properly simulated in conventional process simulators or need a very detailed knowledge of the specific phenomena in order to accurately predict the related consequences. On the other hand, it is not in the intention of the company to completely shutdown a given plant section in order to perform major equipment replacement.
For this reason the most effective amongst the suitable enhancements have been detected according to the SIBUR needs as better detailed here below.

4. Results

Thanks to the energy analysis performed via the Aspen HYSIS simulation flowsheet several design alternatives have been found. In particular, the coupling of the economic assessment allowed to detect the most profitable solutions among all those resulting in a lower energy demand.
As already explained in section 3, only the most relevant among the obtained solutions will be actually carried out on the plant under analysis. In particular, two main measures have been detected as those who contribute to recover more than the 25 % of the overall energy consumption. Those solutions are namely the installation of additional heat exchangers in the LPG section and the installation of a new line connecting the Propane DeHydrogenation (PDH) section and the LPG one. The improvement provided by each of these design solutions are discussed in detail in the following sections. In particular, the energy savings as well as the operational advantages and the economic improvements are commented. Moreover, in order to provide an idea of the

impact of the energy management optimization in terms of environmental benefits, the equivalent CO_2 emissions corresponding to the lower steam demand are reported as well.

4.1 Heat recovery

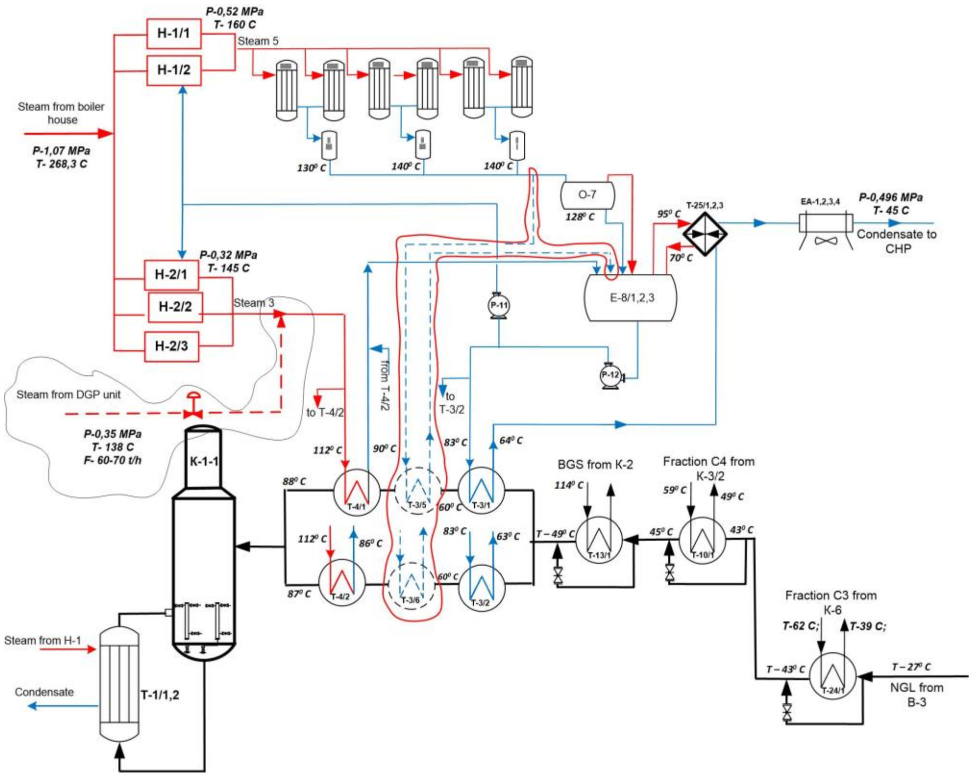

Figure 2: Installation of additional heat exchangers

The most relevant improvement that can be applied to the LPG section is the addition of a third heat exchanger to preheat the distillation column feed as shown in Figure 2. It is worth remarking that two lines in parallel can be seen since one line works while the other one is under maintenance.
The additional heat is provided by the hot condensate lines downstream the reboilers section before reaching the tank E-8/1,2,3. Several benefits derives from this design choice, namely:

- It prevents the formation of steam in tank E-8/1,2,3 and its loss to the atmosphere (up to 40 552 tons of condensate per year);
- It considerably reduces the electricity consumption of coolers EA-1,2,3,4 (160 000 kWh/year);
- It lowers the amount of makeup steam to be provided to the at heat exchangers T-4/1,2,3,4 (cf Figure 2) up to 24 008 Gcal/year that correspond to an equivalent reduction of the CO_2 emissions up to about 6 292 ton-eq per year.

As it can be noticed, the addition of a single heat exchanger deriving from the results of the plantwide pinch analysis positively affect not only the heat duty demand but also the costs deriving from the operations needed to reduce the emissions to the atmosphere.

4.2 Steam integration

The second best measure aimed at improving the plant efficiency resulted to be the installation of a new steam line connecting the PDH site with the LPG one as shown in Figure 3. This solution was selected as one of the best since it provides benefits to both the sections involved.

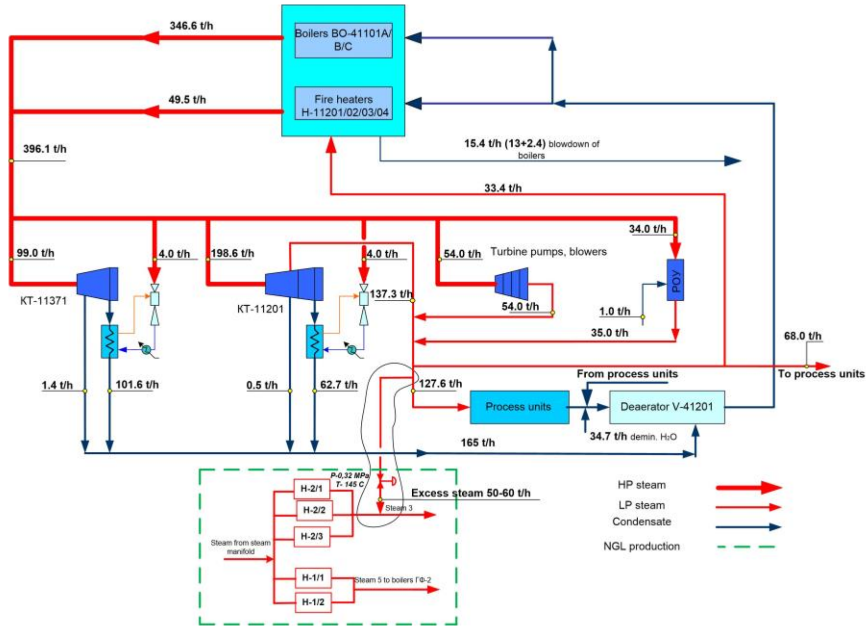

Figure 3: New steam line installation

Even in this case, several advantages can be detected as detailed in the following list:

- Limiting factors of the PDH site that constrain the production to a maximum value equal to the 108% of the nominal production capacity can be overcome;
- It allows a more effective use of steam in the headers 2/1, 2/2, 2/3 resulting in energy savings up to 876 000 Gcal/year corresponding to an equivalent reduction of the CO_2 emissions up to 229 570 ton-eq per year;
- It opens opportunities for a further optimization of the columnar equipment operation for the production of PDH.

Before commenting the economic indicators, it is worth specifying that no third design alternative has been included since the most relevant among the remaining measures implied a substantial modification in the plant layout and the following one didn't provide a considerable improvement.

Finally, Table 1 shows the investment required for each of the two possible solutions and the corresponding economic indicators that prove the profitability of the design solution. They are namely the CAPEX or investment, the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Pay Back Period (PBP). Further details about the way these indicators are calculated can be found in Brennan (2020).
The higher profitability of the first solution is due to the fact that, even if the energy savings are lower than the second alternative, there is a considerable reduction of the electricity consumption that, in terms of operating costs, is more valuable than heat. In any case, both the alternatives result in an IRR higher than 25 %, that is the SIBUR company goal for the plant revamping.

Table 1: Economic Indicators

	Investment [$]	NPV [$]	IRR [%]	PBP [y]
Heat exchanger	490 320	830 820	40.8	4.5
Steam line	544 800	394 980	27.8	5.9

5. Conclusions

The research work performed in collaboration between the SuPER Centre and the SIBUR Company has successfully provided the desired results. By means of an accurate energy analysis, it was possible to improve the performances, and thus the profitability, of an existing LPG section of the SIBUR facility in Tobolsk.

In particular, it was possible to reduce the energetic waste by applying some non-invasive modifications and adding a few pieces of equipment.
The economic analysis allowed to check the benefits of the possible modifications and to make a comparison between them. With the help of some economic performance indicators, such as NPV, IRR and PBP, it was indeed possible not only to prove the rentability of the investments related to the proposed design solutions but also to detect the most profitable ones among them.
Besides the practical interest in the reduction of plants operating costs, this study shows that chemical plants designed decades ago can be further optimized according to new technologies and methodologies by applying poorly invasive modifications respecting the companies guidelines in an effective way. In fact, it usually happens that only a few of the optimal solution applications are enough to enhance the plant performances by more than the 50 %.

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