OPPORTUNITIES TO RECOVER ENERGY IN PETROLEUM REFINERIES

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Abstract. *The petroleum refineries, as the viewpoint of transformation industries and compared to some other industrial sectors, have significant energy consumption. The petroleum process refining can be resumed in five steps: separation, thermal and catalytic cracking, hydrocarbon combination and rearrangement, treatment and product moisture and, finally, special products, for example, lubricants. Recent studies about rational use of energy in refineries identified the need of expansion in the cogeneration activities, which can save 17% of total energy consumption in the plant, in addition to the process that operate at high temperature and pressure; that is the case, for example, of selecting recovery turbine in fluid catalytic cracker and hydrocracker process, which provides an increase in the useful energy in the refine process. In this context, it is interesting to aggregate the energy recover potential from residual gas emission, which it is normally burned in flares, representing a double undesirable situation: energy wastefulness and environmental impact. Refineries are structures with limited flexibility, whose operation depend on characteristics of processed petroleum and final products. However, with the increase of heavy crude participation and the necessity of maximum availability of refinery plant, modifications and aggregation of new processes make them more complex. The incorporation of these modifications, in general, has the focus in the market, not in the system operational conditions, and according to the design philosophy administration, the rational use of energy assumes variable levels of importance. This paper discuss some ways to increase the energy efficiency in the petroleum refinery considering technological elements and potentials of capital and resource savings for improving the energy integration and, consequently, to mitigate environmental impacts.*

Keywords*: rational use of energy, cogeneration, energy recovery*

1. INTRODUCTION

The petroleum refining industry can be understood, in general, as energy inefficient, when compared with the performance of best refineries average (Milosevic and Cowart, 2002). This conclusion was achieved by KBC Company, which domain an analysis methodology based on its experience in the petroleum refining. According to Milosevic and Cowart (2002), many European and American refineries consume 50% more energy than an optimized plant designed and built today. There are many circumstances driving to the high energy consumption, mainly the following:

- the refinery design was done when the energy cost had a low impact;
- low integration in older plants;
- optimization failures in expansions and/or retrofitting;
- modifications not focused in energy conservation;
- low in-house cogeneration efficiency.

Goyal (2001) suggests guidelines, checklists and integrated approach for an energy conservation program designed to petroleum refineries, based on studies that indicates the potential of 10-30% energy savings, in which 5 to 10% met through short-term simple measures and 10 to 20% by means of medium-term measures.

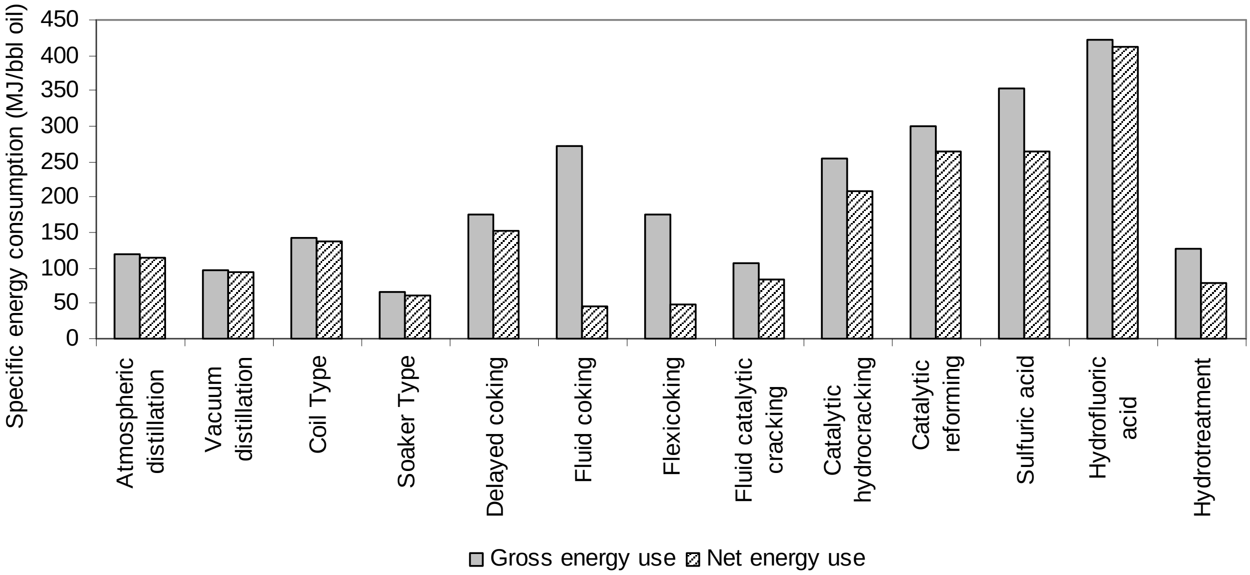
Studies about rational use of energy in refineries identified the need of expansion in the cogeneration activities, which can save 17% of total energy consumption in the plant, in addition to the process that operate at high temperature and pressure; that is the case, for example, of selecting recovery turbine in fluid catalytic cracker and hydrocracker processes, which provides an increase in the useful energy in the refine process (Milosevic and Cowart, 2002).

From these facts, it is possible to recognise that exists opportunities in energy and capital saving and, consequently, mitigating the environmental impacts. The energy efficiency of petroleum refineries seems to be a dominated theme, but the reality indicates the opposite scenario. For example, the US Environment Protection Agency promoted in February 2006 the first meeting of the ENERGY STAR Petroleum Refining Focus, in Houston, Texas, for discussing oil refinery plants challenges; the orientations and proceedings are under development (EPA, 2006).

This paper discusses some ways to increase the energy efficiency in the petroleum refinery considering technological and operational elements. In the oil refinery plant it is possible to improve many processes that involve heat exchange, combustion, steam use and generation, electricity use and generation and human decision, as will be presented.

2. ENERGY USE IN THE REFINING PROCESS

The petroleum process refining can be resumed in five steps: separation, thermal and catalytic cracking, hydrocarbon combination and rearrangement, treatment and product moisture and, finally, special products (as lubricants, for example). Figure 1 presents the typical specific energy consumption (MJ/bbl)[a] in these processes, based on an analysis developed by US Department of Energy (DOE, 1998).

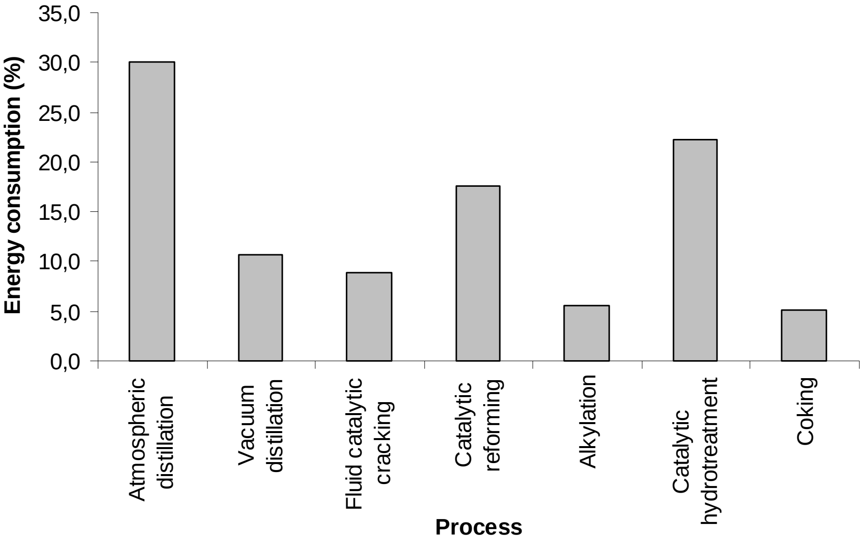


Source: DOE, 1998

Figure 1. Specific energy consumption average in the US petroleum refineries, considering most important process.

It can be observed that absolute energy consumption depends on processing plant capacity. For example, the fig. 2 shows the distribution of energy use in a US typical petroleum refinery, in the qualitative way (DOE, 2000). Note that, in this situation, the atmospheric distillation represents the major consumption, followed by hydrotreatment and by reforming catalytic.

The petroleum refineries capacity depends on its technology, operation time (age) and flexibility, but nowadays it achieves 500,000 barrels per day.



Source: DOE, 2000

Figure 2. Energy consumption average in the US petroleum refineries, considering most important process.

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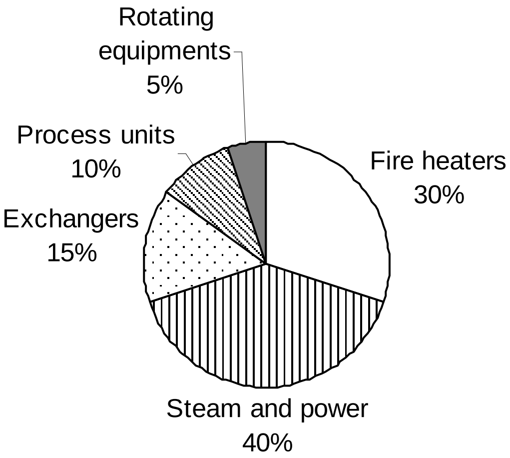
[a] bbl: barrel; the barrel volume is 0.158987 m^3.

3. ENERGY CONSERVATION IN REFINERIES

A lot of plants that processes petroleum was designed and built in the 1960's and their operation is, nowadays, twice or more energy intensive compared to a modern oil refinery. In many cases, their actual consumption is higher than their own designed values, mainly due to (Goyal, 2001):

- non-optimized operation;
- inadequate operation and maintenance;
- lack of engineering support;
- risk of taking crucial decision;
- barriers to modernization;

Actions for energy management require a multidisciplinary approach because the boundaries among several systems has a significant interdependence; as an example, when controlling the gases emission, it can be observed a combustion quality improve, or even the water reuse may be associated to some heat exchange effectiveness improvement. Davis Junior and Knight (2005) indicated some points that must deserve more attention in terms of energy conservation in a petroleum refinery. Figure 3 illustrates the opportunities in saving energy, according to them.



Source: Davis Junior and Knight (2005)

Figure 3. Potential opportunities in save energy in a petroleum refinery.

The petroleum refinery energy use evaluation does not require sophisticate analytical tools, but it is fundamental to understand the process complexity and the subtle relationship between productive systems and operation. In this point, it is necessary to review the efficiency evaluation methodology and to promote a better visibility of ideas and results in each implemented action inside the plant.

3.1. Energy recovery opportunities and discussions

Considering the petroleum refining process, the most significant energy consumer are furnaces, which represent approximately 50% of the total thermal energy consumed. Kosobokova and Berezinets (2001) describe that the heat from the gases going out of the furnaces at high temperature (300 – 500 ^{o}C) is usually not utilized. In this condition, the furnaces operate with efficiency of 58 to 59%, and recovering the lost energy, the efficiency can assume 88%.

In the furnaces operation the main fuel is process gases[b], while hydrogen-containing gas is usually burned in the flare. In both situations, low efficiency conversion (combustion in the furnaces) and waste energy are present. One option to improve the energy use is to consider gas turbines installations, as proposed in fig. 4, where process gases are converted in electric power and the exhausts gases are directed to furnaces.

Exhausted gases have a significant amount of oxygen if the gas turbines operate at high air-fuel ratio, and high temperature heat flux (in the range 420 – 550 ^{o}C) that can be introduced with the air combustion of furnaces. It is interesting to evaluate, in the sequence, the possibility of inserting a heat recovery steam generator between the furnace and the stack for generating low pressure steam and/or hot water (Kosobokova and Berezinets, 2001).

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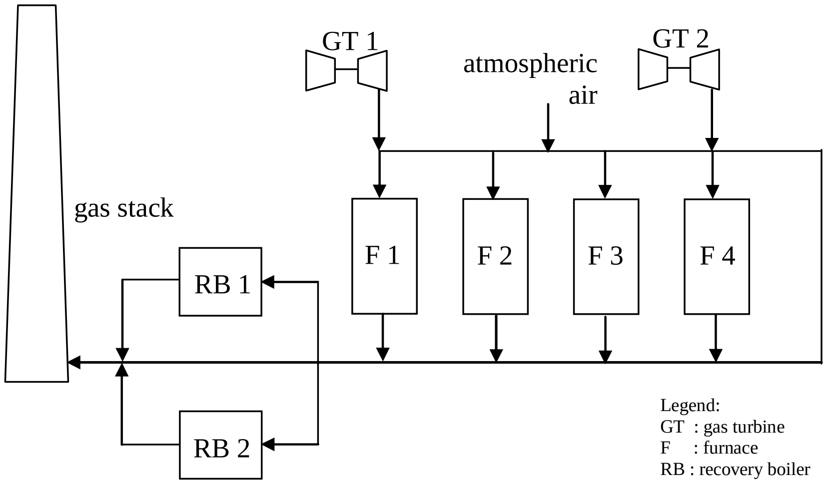
[b] During oil refining operation different process gas composition are formed, which can be subdivided in hydrocarbon, hydrogen-containing and a moisture of both.



Source: Kosobokova and Berezinets (2001)

Figure 4 – Simplified representation to energy recovery in the furnace system in oil refinery.

Beyond of technical aspects, it is necessary to understand the energy and raw-material flow; it is also important to identify the balance points in the refinery operation by means of thermoeconomic optimization of the energy supply-conversion-utilization system, for example (Frangopoulos et al., 1996). Using optimization techniques, the operation acquires flexibility and better adjusts the energy use, final products and environmental impacts. Frangopoulos et al. (1996) detach the follow initiatives applied to the utility sector:

- electricity can be produced either by the gas turbine or by the steam turbine, at optimum load distribution;
- gas turbine systems produce electricity and steam at the same time. Thus, the increase of gas turbine participation results in an increase of steam availability, reducing the required steam production of the steam boilers;
- increasing the level of electricity production by steam turbine generation results in reduced steam availability, thus increasing the required production of steam boilers;
- electricity can be exported to the national power grid according to its availability and price, but it affects gas turbines, steam turbines and steam generators operation;
- steam production and consumption at different levels must be kept in balance to avoid degrading steam quality;

The petroleum refineries can still provide some opportunities of energy saving by rearranging equipments and/or incorporating more efficient devices supervised by informational systems (IT), but the main barriers are offered by conceptual misunderstand, operational failures and personal opposition to the changes. It is important to note that these points are included in the action with minor capital in terms of investment. On the other hand, in several opportunities, it does not represent significant saving, although it can move the professional team toward sophisticated interventions.

Sometimes, some process information is lost by inadequate data manipulation or by partial understanding of “cause and effect” relationships. As an example, the availability of a data set of process steam flow at different pressure levels in an hourly or monthly time-series for several years may be under-evaluated if the analysts consider it only for computing a general index and not observe some particular facts, such as process instabilities and peaks or valleys, that reveals the qualitative aspects of the analysis. In this situation, they lose the opportunity of using some other tolls that can provide the best evaluation of irreversibilities (losses) and/or to attribute the correct weight to the process variables.

In the next topic, it will be presented the impact of cogeneration inside petroleum refinery operation and, consequently, how to improve the energy use not only by simultaneous power and steam production (traditional concept), but applying the cogeneration aimed to specific production systems.

3.2. Cogeneration

The average potential of energy efficiency improvements – in which cogeneration is one of the most feasible options – on a worldwide basis is supposed to be close to 30% and in this value 17% is attributable to cogeneration and 13% to refinery fuel savings (Milosevic and Cowart, 2002).

These authors also argument that this value is conservative, because it assumes that refineries only cogenerate power to meet their own demand, using only a fraction of the available heat sink. In this way, it is believed that this potential is higher, especially because in cogeneration analysis it is usually assumed that part of the wasted heat is devoted to steam consumers, but additional application of cogeneration as the pre-heating of crude oil or even its exhaustion into crude oil furnaces is also common.

For Milosevic and Cowart (2000), the refinery thermal demands are the key to the refinery success, and additionally they state that to fully realize the potential of cogeneration some surplus power must be generated on site to be exported. Haworth et al. (2000), however, pointed out that the cost effective potential of cogeneration is often very high and it can be economic to generate electric power even if there is only limited use for steam in the process.

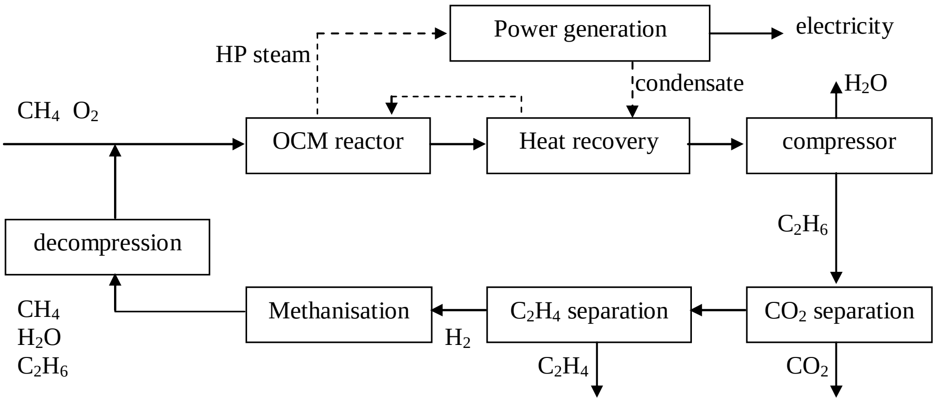
Nowadays, the care devoted to the reduction of CO_2 emissions is mandatory, and in the petrochemical industry it is a special worry for which the attractiveness of some more efficient advanced technologies may be reduced in the case of augmenting CO_2 emissions; fortunately, advanced technologies under development are based on cogeneration concepts, whose premises involve more produced thermal and electric power with less fuel combustion.

Klemeš et al. (1997) presented a methodology of process integration that considers cogeneration and CO_2 emissions, reporting savings in fuel of up to 20% and improvements of at least 50% in global CO_2 levels and other emissions levels when compared to the improvements obtained by application of individual industrial processes. Phylipsen et al. (2002) realized an energy efficiency analysis for the Dutch industry based on the energy efficiency index (EEI), a concept usually utilized in the petrochemical sector but in this case extrapolated for some other sectors, as iron and steel, pulp and paper, and public electricity generation; for the petrochemical sector, ethylene production (C_2H_6) was particularly considered. In an actual, static benchmarking analysis on energy use and CO_2 emissions for the petrochemical sector that considered all the European producers, Japan, Korea, the United States and countries in South America, the authors concluded that petrochemical (energy savings compared to the frozen efficiency level of 22 to 26 PJ and CO_2 emission reduction compared to autonomous efficiency improvement of 1.3 to 1.6 Mt) and electric generation (41 to 64 PJ and -0.6 to 2.8 Mt, respectively) were the sectors where most of the savings are expected.

The use of gas turbines to produce power and hot exhaust gases for heating cracking furnaces is proposed by Albano, Olszewski and Fukushima (1992) as an attractive solution of reducing energy requirements of ethylene production. As the cracking furnace area is recognized as the largest energy consumer in an olefin plant, the association of cogeneration results in the reduction of substantial amounts of energy.

As polymerization operations need electric and thermal energy in significant amounts, Budin et al. (2006) developed an analysis of a combined heat and power production for the production of low density polyethylene (LDPE) that achieved savings in purchased electric energy of 17.6%. In a comparison between a backpressure steam cycle cogeneration scheme and separated generation of electric and thermal energy, the first achieved 16 to 24% savings and the latter 5 to 7.3%.

Cogeneration of ethylene and electricity through oxidative coupling of methane is proposed by Hugill et al. (2005). The authors compared a cogeneration scheme with a scheme in which ethylene and electricity were generated separately by conventional processes. Cogeneration schemes for ethylene and electricity were previously suggested by Penninger[c] (1996, apud Hugill et al., 2005) but subsequently studied by Swanenberg[d] (1998, apud Hugill et al., 2005), that proposed two options: the fist one (fig. 5) is an ethylene plant with electricity as co-product and the second one is an electric power plant with ethylene as co-product, not evaluated in the paper but presented as an interesting electricity producer to be considered when connection to the grid is feasible.



Source: Hugill et al. (2005)

Figure 5– Cogeneration scheme proposed for ethylene and electricity production.

Cogeneration scheme is based on the use of OCM (oxidative coupling of methane) fluidized bed reactor that operates at 800°C and 101 kPa, generating high pressure (HP) steam. Power generation is generated in a conventional condensing steam cycle. The separated scheme considered a 43% efficient (based on high heating value) coal-natural gas mix (50/50%) as representative of Dutch power generation park and an ethylene cracker. As conclusion, the

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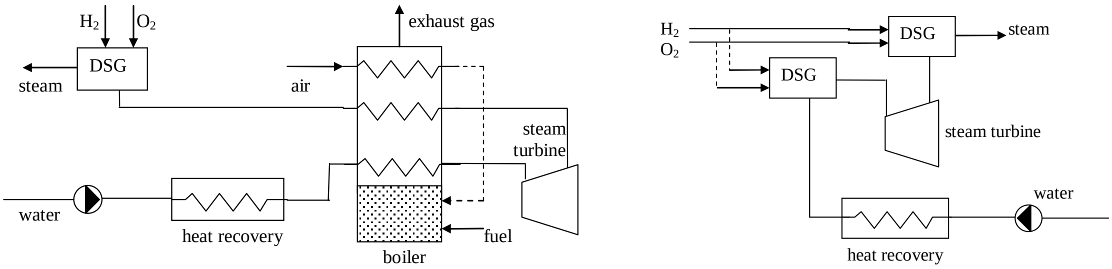
[c] Penninger, J.M.L., 1996, “Co-generation of olefins and electric power”, Environmentally Benign Chemical Processes, Polanica, Poland, 1996.

[d] Swanenber, G.M.J.M., 1998, “Cogeneration of ethylene and electricity with oxidative methane coupling: study of technical feasibility and economic merit”, Eindhoven University of Technology, Eindhoven, August 1998.

considered scheme didn't present significant energy savings, but CO_2 emissions were significantly reduced; unfortunately, at today's prices – and without surplus electricity production to be commercialized – the proposed cogeneration scheme was considered less attractive than isolated processes.

The concept of cogeneration of power and hydrogen is attractive for the petrochemical sector because the use of both – especially hydrogen – is very high: catalytic hydrocracking consumes 362.10^3 to 904.10^3 MJ/bbl of crude oil and catalytic hydrotreating consumes 235.10^3 MJ/bbl of crude oil (DOE, 1998). Spazzafumo (2004) proposed two different solutions for increasing the steam temperature: a hybrid steam post-superheating cycle that uses hydrogen and oxygen only to superheat the steam for fuel processor (fig. 6a), and a hydrogen/oxygen backpressure cycle that uses hydrogen and oxygen for the whole thermodynamic cycle (fig. 6b).



(a) (b)

Note: DSG - direct steam generator

Source: Spazzafumo (2004)

Figure 6– Cogeneration schemes proposed for hydrogen and electricity production

A final note about the use of fuel cells for the cogeneration of electricity and organic chemicals deserves to be mentioned. Yuan et al. (2001) and Yuan et al. (2005) describe the use of polymer electrolyte fuel cell (PEFC) for cogenerating cyclohexylamine and electricity and organic chemicals and electricity, respectively.

3.3. Efficiency evaluation

The energy use in the oil refineries, in common way, is evaluated applying two similar methods developed by Solomon Associates and KBC Consultants, which are calculated as the ratio of actual refinery energy consumption and average energy consumption of best world refineries. The average energy consumption of best world refineries parameter is considered a standard value and is assumed to be 100 per cent, taking into account typical energy use for each refinery process. The actual energy consumption is measured for the refinery processes data. If this ratio assumes values below 100 per cent, it indicates that such plant is more efficient than the average one and, on the other hand, values above 100 per cent means less efficient plant (Phylipsen at al., 2002). For example, a refinery with 150 per cent means that one is 50% less efficient that standard refinery (Milosevic and Cowart, 2002; Nyboer and Rivers, 2002). This analysis tool is an important comparison parameter among oil refineries, and is known as the Energy Efficiency Index (EEI).

Although these analyses are traditional in the petroleum refinery sector and their use is well consolidated, there are some points that need special attention; for example, the sensitivity among energy vectors in the process. In some simulations, it is not clear the effective participation of each energy source, such electricity, process gases and coke, when the energy indicator sometimes do not respond to the changes realized on them. When using the EEI, it is necessary to consider that the use of certain conversion factors from process gas, electricity generated and coke to standard oil barrel are based on specific combustion efficiency whose origin is not clear. The variation of such combustion efficiency may favor some energy sources in detriment of some others and, therefore, the energy consolidation do not capture subtle improvements throughout the time and the final perception about energy efficiency is not evident.

This paper does not have the intention to discredit EEI because it already has its merit, but to suggest aggregating some other tools to help improving the efficiency evaluation. In this point, it is fundamental to understand the transformation processes that are present in the efficiency analysis to identify the boundaries and to have domain on the raw-material, products and energy flows. Once established the system boundary, the Second Law of Thermodynamics (exergetic analysis) reveals a robust tool because it can evidence the refining processes quality by irreversibility indications and the limits by means of improving in the energy use.

Reistad[e] (1970, apud Rivero at al., 2004) considered in his methodology how much exergy can be recovered and its respective difficulty degree. Equation (1) illustrates such analysis, classified as a combined exergetic efficiency parameter ($e_{potential}$):

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[e] Reistad, G. M., 1970, "Availability: concepts and applications". Ph.D. Thesis. The University of Wisconsin, University Micro.lms, Inc., Ann Arbor.

$$e_{potential} = i(1-\varepsilon) + e_{environment} \tag{1}$$

in which:
i: irreversibility inside the control volume;
ε: ratio between useful exergy and total inlet exergy at control volume;
$e_{\text{environment}}$: exergy rejected to the environment;

A high value of $(1–\varepsilon)$ means easiness in improving exergy utilization, taking into account the internal irreversibility relatively to an evaluated system. In a priorities scale, interventions must be initialized by systems with high $e_{\text{potential}}$.

Figure 7 illustrates the exergy efficiency use, where the control volume defines the analysis boundary. A complete evaluation is discussed in Rivero et al. (2004), but the main idea is to define the furnace internal irreversibility, taking into account the specific exergy flows (mechanical and chemical) at the boundary. A complete analysis requires the displacement of control volume for inside furnace (for example, considering the thermal change surface between hot gases and raw-material); it is necessary to consider that as deep as the analysis, more costly the evaluation will be and more development time will be required.

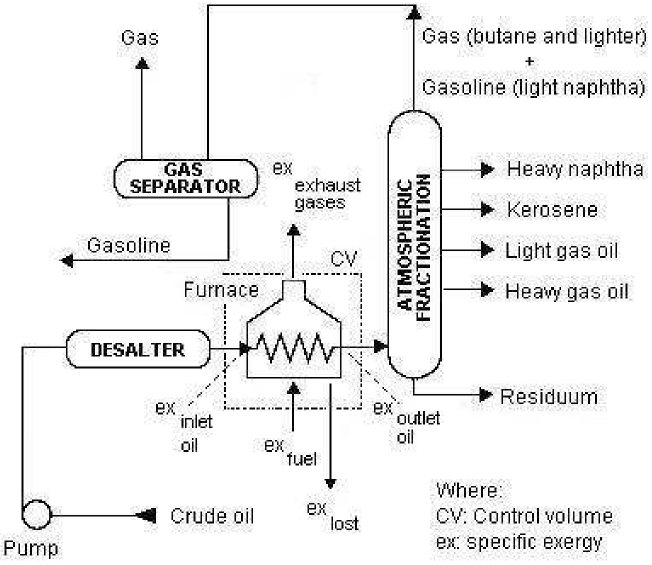

Figure 7 – Example of exergetic efficiency application in an atmospheric distillation furnace.

Adopting the exergy analysis together EEI methodology, it is possible to compare the performance among petroleum refineries (traditional way) and, if some plant does not get to reach the desired goal, it is possible to locate where irreversibilities are occurring. Based on these results, decision-makers can establish an action plan aimed to manage improvements, operation adjusts and some others activities oriented to mitigate the destroyed exergy.

4. FINAL CONSIDERATIONS

The petroleum refineries are operated based on EEI, but the energetic and environmental requirements stimulate the decision makers to look for another analytical tools aimed to measure the energy efficiency. The more it goes in direction to energy efficient use the more challenges appears because physical constraints become more significant and it is necessary to improve the energy analysis. The Second Law of Thermodynamics supplies conceptual elements that conduct to consistent evaluations in terms of the process quality and natural constraints considerations.

In this point of view, many improvements can be implemented but it is important to have in mind that the production system integration must be enhanced either for utility sector or the steam trap operation. In this context, cogeneration extrapolates its participation in the oil refining from electricity and steam supplier to direct agent inside the production, interacting with raw material.

Technical solutions are something feasible based on solid concepts and respecting good practices and material limitations. Together with technical solutions, operational management activities are desirable because people participation is the basis to new conceptions for the petroleum refinery plants, amongst which understand and employ other analysis tools.

Unfortunately the references about refineries performance and operation belong to oil and consultants companies; however, the activities complexity is increasing due to integration needs and environmental constraints. Considering these facts, the partnership with universities, for example, has been a way for applying alternative analytical tools. Specific information is limited by the following reasons: some projects (and respective results) present confidentiality restrictions imposed by contract, and also by the fact that the evaluation of energy opportunities for petroleum sector is nowadays under development and, hence, without consolidated results yet.

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