EXERGETIC EFFICIENCY FOR STATIONARY OIL PRODUCING UNITS

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Abstract. *This work presents a methodology to evaluate the energetic efficiency of Oil and Gas Production Units based on the exergetic analysis method. The concept of exergetic efficiency is used to evaluate the unit energy consumption based on the transformation potential of the involved energy amounts taking its actual environment as the reference and to evaluate the best exergetic efficiency that is technologically feasible using tha available producing technology. The concept is used to evaluate the overall unit efficiency as well as the efficiency of each one of its components.*

Keywords*: Exergetic Analysis, Thermodynamics, Oil Production Installations.*

1. INTRODUCTION

As is well known, oil and gas producing units have a large quantity of different components. Each one of these components operates with a different form of energy, such as chemical energy from fuels, electrical energy and thermal energy, and adopts also a specific producing method in order to perform a specific task.

Typically, the performance evaluation of such units is based on the energetic efficiency. This efficiency is calculated as an overall parameter of the whole unit as well as an individual parameter for each one of its components. In general, the efficiency is calculated comparing the ideal amount of energy necessary to attain the process desired effect with the effective amount of energy actually used to realize it. The difference between these quantities is regarded as losses due to inefficiencies or to the intrinsic irreversibility of the actual performed process. One specific method is used to calculate the performance of each component. As a result it is not always possible to compare the efficiencies of each individual component in order to optimize the performance of the whole plant. This energetic efficiency analysis is based on the first law of thermodynamics, without taking into account the intrinsic quality of the energy losses to the environment. In general, oil and gas producing units can exchange large amounts of energy with their environments. But the energetic efficiency so calculated may not be used to properly compare the performance of different units operating in the same environment or of equal units operating in different ones.

Another method to evaluate the efficiency of a producing unit is based on the transformation potential of the amount of each form of energy involved with the process. This transformation potential is measured taking the environmental condition as a reference. It is called exergy. The exergy method establishes a common ground to compare the potential to do work of the different forms of energy involved in pursuing the overall task of the unit and the specific task of each of its components. Compared with the energetic analysis, the exergetic analysis produces more information concerning alternative possibilities for the design of new units or for adopting operational and structural changes in existing ones.

The first objective of this paper is to describe a method for the determination of the actual overall exergetic loss or exergy consumption of oil producing plants and for each one of its components. The second objective is to establish a possible minimum overall exergetic consumption for the unit, i.e., the technically feasible maximum unit exergetic efficiency. This maximum corresponds to the most efficient use of the involved energy resources to be obtained with the available technology. The analysis uses the exergy of the input and output energy fluxes, calculated from the point of view of an external observer to a convenient defined control volume (Ghiorzi, 1997). The exergetic efficiency calculation refers to the actual configuration of a certain design or to the real operational conditions of an existing unit, whereas the proposed reference calculation refers to the state of the art of the available producing technology. The proposed analytic model establishes a technically feasible reference for the maximum exergetic efficiency of a stationary producing unit. Although it is not done in this work, the model can be extended to take into account economical aspects related to the exergy fluxes across the boundaries of a control volume involving the unit or each one of its components. It is thus believed that the proposed method represents a more realistic and global basis for the evaluation of oil and gas producing units.

2. MAIN SYSTENS OF OIL PRODUCTION UNITS

The model is limited to the unit’s main systems in terms of sources and demands of exergy. Each one of these systems transfers exergy to the unit’s products or acts as a kind of exergy source to the unit (Neves, 2008a). In the most common configurations, these unit’s systems are the oil treatment and transfer system - including the water discard component; the gas compression system; the electric energy and hot water generation system; and the water injection system.

The oil treatment and transfer system receives the crude oil flux from the submarine producing wells. The oil is processed in order to attain a given BSW (basic sediment and water) specification. Basically, this system separates the incoming crude oil into gas, oil and water, directing each one as a separated stream to its destination.

The gas flows to the gas compression system. From there it can be exported to onshore consumers, or can be re-injected in the subterranean reservoirs through submarine injecting wells; it can be also used to gas lift. The re-injection is a way of postponing the gas utilization and the gas lift is the most common method of oil artificial lift.

The oil is delivered to transfer pumps. From there it is pumped to other units, or to storage ships or pipelined to the shore.

The produced water flows to a specific treatment system. The residual oil extracted is sent back to the oil treatment and the clean water is discarded.

The water injection system is responsible to capture seawater, treat it and inject it into the producing reservoir, trough the sub-sea injection wells. The purpose of this water injection is to maintain the reservoir static pressure, in order to keep the liquid producing levels during the unit's life cycle.

3. APPLICATION OF EXERGETIC ANALYSIS TO OIL PRODUCTION UNITS

An oil production unit can be described as an open system. The mass flux input is the flux of a mixture of oil, gas, water, sand and other contaminants and the mass outputs are the streams of natural gas, specified oil and produced water. The control volume to a unit external observer is showed in Figure 1. The feed power can be obtained through:

- Burning of the produced gas;
- Burning of other fuels (external in relation to the plant), typically diesel;
- Electrical energy from the concessionary, or generated on other unit.

The exergetic analysis of a system takes into account the exergy of the input streams, the exergy of the output streams, the process irreversibility and the losses to the environment. The oil production unit must maximize the production with a minimum feed exergy. In other words, it has to operate with a minimum exergy destruction and minimum losses to the environment. It is also desired that most of the feed exergy follows to the unit's products streams. The chemical reactions that occur in the unit in order to separate the input stream are minimal. Then, the chemical exergy of these streams are not considered, because, there are almost no changes in the chemical exergy of the output streams in comparison with its amount in the input.

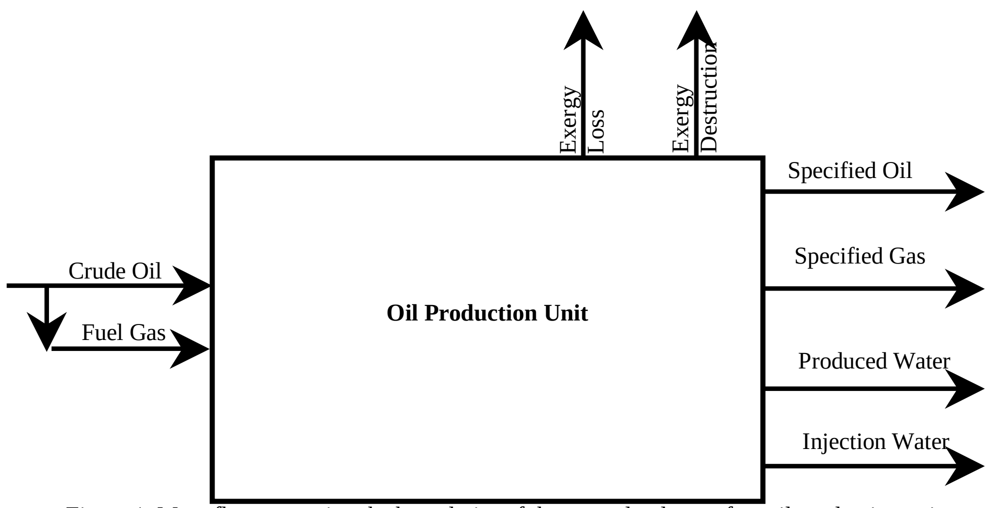

Figure 1. Mass fluxes crossing the boundaries of the control volume of an oil production unit.

The physical exergy of crude oil input stream and of the output streams takes into account the entalphic exergy and also the potential exergy and the kinetic exergy of the streams. The so calculated exergy is called thermomechanical exergy. But, this procedure is common only in part of the revised technical literature (Neves, 2008b). Likewise, only the enthalpic exergy is considered in this work. The calculation of potential and of kinetic exergy fluxes requires the knowledge of very specific characteristics of a real unit. In this case, they could be calculated without difficulty and not considering then doesn't affect the consistence of the proposed method.

Two kinds of main systems are considered to describe the unit. First, there are the systems that transfer exergy to the outputs fluxes or are exergy sources to the unit. Second, there are the auxiliary systems which do not transfer exergy to those fluxes or that are not exergy sources. Examples of this second kind are the ones responsible for chemical injections and for seawater delivery, as well as the work and sleep rooms. The exergy consumed in these systems are considered feed data.

In order to calculate the specific energy, the environmental conditions taken as reference are the pressure at sea level, 101.325 kPa, and a temperature of 25^oC (Neves, 2008c). The necessary thermodynamic properties of the input and output fluxes are determined based on the following conditions, assumed just to set up the model:

- The crude oil that enters the unit crosses the control volume on the unit crude oil manifold, upstream to the heat exchangers and to the oil separation system;
- The specified oil to be exported crosses the control volume just immediately downstream of the oil transfer pumps;

- The natural gas to be exported or to be directed to the gas lift process crosses the control volume just immediately downstream of the last stage of the gas compressor systems;
- The separated water crosses the control volume with atmospheric pressure and at the same temperature of the oil separation process;
- The injection water crosses the control volume just immediately downstream of the water injection pumps.

4. EXERGETIC EFFICIENCY BASED ON THE DEGREE OF THERMODYNAMIC PERFECTION

The exergy balance can be written in terms of the following fluxes:

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \qquad (1)$$

The meaning of each term is:

$\dot{E}_F$ – Fuel exergy flux.

$\dot{E}_P$ – Product exergy flux.

$\dot{E}_D$ – Destroyed exergy flux.

$\dot{E}_L$ – Loss exergy flux.

The exergetic efficiency ε is defined as:

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = 1 - \frac{\dot{E}_L + \dot{E}_D}{\dot{E}_F} \qquad (2)$$

The exergetic efficiency is also called thermodynamic degree of perfection of the process, Szargut (1988). Synthetically, it means that a process is more “perfect” than another one if it destroy less transformation potential, i.e., if the difference between the input and output exergy fluxes is smaller. For the purpose of the present analysis, the balance of the exergy fluxes assumes the following qualitative form:

Crude oil physical exergy input + fuel gas physical exergy input = main products physical exergy outputs + exergy consumed as eletricity on the auxiliary systems + exergy loss and exergy destruction (3)

It follows then:

$$\dot{E}_{CO} + \dot{E}_F = (\dot{E}_o + \dot{E}_g + \dot{E}_{PW} + \dot{E}_{IW}) + (\dot{E}_{outros} + \dot{W}_{Aux}) + (\dot{E}_L + \dot{E}_D). \qquad (4)$$

The meaning of each term is:

$\dot{E}_{CO}$ - Flux of the physical exergy of the crude oil that enters the unit, considered a fuel;

$\dot{E}_F$ - Flux of the chemical exergy of the fuel gas, considered a fuel;

$\dot{E}_o$ - Flux of the physical exergy of the specified oil, considered a product;

$\dot{E}_g$ - Flux of the physical exergy of the separated natural gas, considered a product;

$\dot{E}_{PW}$ - Flux of the physical exergy of the produced water, considered a product;

$\dot{E}_{IW}$ - Flux of the physical exergy of the injection water, considered a product;

$\dot{W}_{Aux}$ - Electrical power consumed in the auxiliary systems.

Physically, the flux of destroyed exergy doesn’t cross the unit’s control volume. Considering all the unit’s exergetic consumptions as products, the exergetic efficiency of the unit can be written as:

$$\varepsilon = \frac{(\dot{E}_o + \dot{E}_g) + (\dot{E}_{PW} + \dot{E}_{IW} + \dot{W}_{Aux})}{\dot{E}_F + \dot{E}_{pet}} . \quad (5)$$

Although the exergy of the produced water or the exergy consumed in the auxiliary systems actually are not exergy of the products of the unit, they must be assumed as so in order to make it possible to compare the performance of different units. For instance, if the produced water would not be taken as a product, a plant that process crude oil with 80% of water content would be seem as less efficient than other that handles crude oil with 20% of water content. For the same reason, a unit that has high auxiliary systems exergy consumption, due to its products characteristics – for instance, a high concentration of sulphur, would be under evaluated if compared with simpler units. But, as these characteristics are too particular of each real unit, for the determination of the plant exergetic efficiency it is considered as products only the specified oil, the separated gas, the produced water and the injection water. It follows:

$$\varepsilon_{\Pr inc} = \frac{(\dot{E}_o + \dot{E}_g) + (\dot{E}_{PW} + \dot{E}_{IW})}{\dot{E}_F + \dot{E}_{CO}} . \quad (6)$$

The exergy consumed in the auxiliary systems is considered by means of a particular indicator that shows its relative influence compared with the total input of exergy.

$$\chi_{Aux} = \frac{\dot{W}_{Aux}}{\dot{E}_F + \dot{E}_{co}} \quad (7)$$

In analogy, another indicator is used to evaluate the exergy loss and destruction of exergy:

$$\chi_{E_{L+D}} = \frac{(\dot{E}_L + \dot{E}_D)}{\dot{E}_F + \dot{E}_{pet}} \quad (8)$$

To separate the exergy loss of the destroyed exergy it would be necessary to quantify the losses, due to flaring; losses on the machine exhausts, and the thermal exchange with the environment. This calculation procedure is too specific for the purpose of a general methodology. But they can be estimated as a difference, as follows:

$$(\dot{E}_L + \dot{E}_D) = (\dot{E}_F + \dot{E}_{CO}) - [(\dot{E}_o + \dot{E}_g) + (\dot{E}_{PW} + \dot{E}_{IW}) + (\dot{W}_{Aux})] . \quad (9)$$

5. EXERGETIC ANALYSIS APPLIED TO DESIGN OR TO EXISTENT OIL PRODUCING UNIT

5.1. Calculation of the Fuel Exergy

The fuel exergy of the unit is basically the chemical exergy of the gas used to generate electrical power. Eventually, this power is used to drive the compressors and to furnaces. A small amount of the fuel exergy is due to the physical exergy from the incoming crude oil.

The calculation of the gas turbines mass flow rate, $\dot{m}_{FGT}$, requires the knowledge of their thermodynamic efficiency, η_{GT}, of the low heat value of the gas, LHV, and of the total electrical power consumption, Pow, consumed on the main and auxiliary systems. It follows:

$$\dot{m}_{FGT} = \frac{Pow}{LHV\eta_{GT}} . \quad (10)$$

The thermodynamic efficiency of the gas turbines is evaluated as a function of its heat rate, HR. The heat rate is a well-known characteristic of this kind of machines, published by the different manufacturers. This parameter represents the necessary thermal energy required in the gas combustion reaction to generate a unit kW of electrical power.

If the gas compressors are driven by gas turbines, the necessary fuel gas flow rate $\dot{m}_{Fc}$ is calculated using its demanded compression power, Pow_C, and the thermodynamic efficiency of the turbo compressors, η_C:

$$\dot{m}_{F_C} = \frac{Pow_C}{LHV\eta_C} . \quad (11)$$

If there are furnaces present on the unit, its necessary fuel gas flow rate, $\dot{m}_{FFU}$, is a direct input data as well as the mass gas flow rate that is burned in the unit flare $\dot{m}_{flare}$. In resume, the fuel exergy can be calculated as:

$$\dot{E}_{F\,Real} = [1{,}037(\dot{m}_{FGT} + \dot{m}_{FC} + \dot{m}_{FFU} + \dot{m}_{flare})LHV] + \dot{E}_{CO}\,. \tag{12}$$

Here $\dot{E}_{CO}$ is the physical exergy of the crude oil. The coefficient 1.037 represents the change from the LHV energy base to the exergy base (Neves, 2008d).

5.2. Calculation of the Physical Exergies of the Input and Output Fluxes

As already mentioned, the exergy of the streams to be used in the calculations corresponds only to their physical part, in such a way that:

$$e_{ph} = (h - h_o) - T_o(s - s_o)\,. \tag{13}$$

The liquid streams - the liquid part of the crude oil, the specified oil, the produced water and the injection water – are considered incompressible. Crude oil exergy between inlet conditions and the reference state:

$$\dot{E}_{CO} = \dot{m}_{CO}(c\Delta T + \frac{1}{\rho}\Delta p - T_o c \ln\frac{T}{T_o})\,. \tag{14}$$

Specified oil exergy between outlet conditions and the reference state:

$$\dot{E}_{O} = \dot{m}_{O}(c\Delta T + \frac{1}{\rho}\Delta p - T_o c \ln\frac{T}{T_o})\,. \tag{15}$$

Produced water exergy between outlet conditions and the reference state:

$$\dot{E}_{PW} = \dot{m}_{PW}(c\Delta T + \frac{1}{\rho}\Delta p - T_o c \ln\frac{T}{T_o})\,. \tag{16}$$

Water injection exergy between outlet conditions and the reference state:

$$\dot{E}_{IW} = \dot{m}_{Iw}(c\Delta T + \frac{1}{\rho}\Delta p - T_o c \ln\frac{T}{T_o})\,. \tag{17}$$

The same analysis can be done to the gaseous streams - associated gas on the crude oil and separated gas, considering that they can be considered as the ideal gas. Associated gas exergy between inlet conditions and the reference state:

$$\dot{E}_{phAG} = \dot{m}_{AG}\{(c_p\Delta T) - T_0[c_p(\ln\frac{T}{T_o}) - R(\ln\frac{p}{p_0})]\}\,. \tag{18}$$

Separated gas exergy between outlet conditions and the reference state:

$$\dot{E}_{phSG} = \dot{m}_{SG}\{(c_p\Delta T) - T_0[c_p(\ln\frac{T}{T_o}) - R(\ln\frac{p}{p_o})]\}\,. \tag{19}$$

5.3. Calculation of the Loss and the Destroyed Exergy

Eq. (9) is used to calculate the loss and the destroyed exergy.

6. DETERMINATION OF A FEASIBLE REFERENCE MODEL

The reference model is used to compare a real situation of exergetic consumption of the oil producing unit with that of a unit operating under ideal conditions. This ideal condition is basically referred to the use of available technologies in the main systems and to the maximum technically feasible thermodynamic and mechanical efficiency of their main equipment - gas turbines, compressors, pumps, electrical motors and electrical generators. Besides, the reference model also looks for a better integration between the exergetic sources and their demands, specially the thermal ones.

The main source of thermal energy is the gas exhaust of the gas turbines of the electrical generation system. Most frequently, this thermal energy is already used as process heat, although its total energy capacity is not expended. This residual capacity can be used to increment the energetic efficiency of the gas turbines by cooling its entrance air with an absorption chiller. Another source of thermal energy is the heat reject in the gas compression system. This heat rejection can be used also to preheat the crude oil before the separation. All these opportunities of using thermal energy are evaluated in the reference model.

The power demands of the main systems are calculated using the maximum feasible thermodynamic and mechanical efficiency.

Electrical power demand of the gas compression system:

$$HP = \frac{n}{n-1} RT_s[(r_p^{\frac{n-1}{n}} - 1)] \quad , \qquad (20)$$

$$\dot{W}_C = \frac{\dot{m}_g\, HP}{\eta_P \eta_{mec}} \quad , \qquad (21)$$

Here:

HP - compressor politropic head (specific work);

n - gas politropic exponent;

R - individual gas constant;

Ts - suction temperature;

Rp - compressor pressure ratio;

$\dot{m}_g$ - gas mass flow rate;

$\dot{W}_C$ - compressor demanded electrical power;

η_P - compressor politropic efficiency (maximum technically feasible 80%);

η_{mec} - compressor system mechanical efficiency (maximum technically feasible 98%).

Electrical power demand of the pump systems (oil transfer and water injection).

$$H = \frac{\Delta P}{\gamma}, \qquad (23)$$

$$\dot{W} = \frac{\dot{m}.H}{\eta} \quad , \qquad (23)$$

Here:

H - pump head of each system (oil transfer or water injection);

ΔP - pressure difference between discharge and suction of each system (oil transfer or water injection);

γ - specific weight of the pumped liquid (water or specified oil);

η - pump total efficiency (hydraulic, volumetric and mechanical – maximum 80%).

$\dot{W}$ - demanded electrical power on each system (oil transfer or water injection).

After the determination of the minimal feasible electrical power demand of each main system, it is possible to calculate the required fuel gas flow rate on the turbo-generators of the electrical power generation system. It follows:

$$\dot{E}_C = (\dot{W}_{Aux} + \dot{W}_{comp} + \dot{W}_{SO} + \dot{W}_{IW}) \frac{HR}{3600} 1{,}037 \quad , \qquad (24)$$

$$\dot{m}_f = \frac{\dot{E}_Q}{LHV}, \qquad (25)$$

where:

$\dot{E}_C$ - minimum fuel gas chemical exergy rate to drive the whole oil producing unit;

$\dot{W}_{Aux}$ - minimum electrical power demanded on the auxiliary systems – input data of the model;

$\dot{W}_{comp}$ - minimum electrical power demanded on the gas compression system;

$\dot{W}_{SO}$ - minimum electrical power demanded on the specified oil transfer system;

$\dot{W}_{IW}$ - minimum electrical power demanded on the injection water system;

HR - minimum feasible gas turbine heat rate, expressed in kJ of thermal energy per kW of electrical power.

One of the most drastic forms of energy inefficiency in oil producing units is the use of furnaces to heat the crude oil in order to separate into specified oil, natural gas and water. Therefore, the methodological purpose on the reference model is to use all the existent thermal energy sources to avoid the need of furnaces.

To attend this goal, the free water stream that does not emulsion in the crude oil stream is first separated from the crude oil. This procedure minimizes the amount of the mass flow rate to be heated. After that, the remaining crude oil stream is heated in counter stream with the already heated specified oil and produced water streams. This procedure is common practice in oil producing units. The model evaluates if the thermal energy content of the gas turbines exhaust gas is enough to heat the crude oil stream up to a temperature in which its viscosity is 10 cst. If this main source of thermal energy is not enough, the model tries to identify if it is possible to use the thermal energy content of the compressed gas in the compression system (Neves, 2008d).

All the involved mass flow rates and the temperatures are evaluated in accordance with the following enthalpy balance:

$$\varepsilon \dot{m}_s c_s (T_{os} - T_{is}) = \dot{m}_d c_d (T_{od} - T_{id}) \,. \qquad (26)$$

The subscripts "s" refer to the heat stream source and the subscripts "d" refer to the heat demanding streams. The subscripts "i" refer to the inlet streams in the heat exchangers and the subscripts "o" refer to the outlet streams out of the heat exchangers. In eq. (26), the symbol "ε" refers to the thermal exchange effectiveness and it is determined to each particular heat exchanger (liquid / liquid, liquid / gas, etc.).

After the evaluation of the energy available in all mentioned thermal energy sources, if this quantity is not enough, the model calculates the minimal fuel rate of the gas to be burned in a furnace to complement the necessary thermal energy demands.

7. CALCULATION PROCEDURES

The first step of the first calculation procedure is to determine the exergy of the products as showed in Section 5. The second step is to determine the fuel exergy and the sum of the loss and the destroyed exergy. At this point, it is possible to calculate the exergetic efficiency and the other parameters shown in Section 4.

The first step of the second calculation procedure is to define the reference model, see Section 6, calculating the fuel exergy and the sum of the loss and destroyed exergies in this reference model. The next step is then to evaluate the exergetic efficiency and the other parameters shown in Section 4. The last step is to compare the exergetic efficiency and the other indexes of the real project or of an existing installation with those of the reference model.

This methodology was implemented in a computational routine written in "C" programming language. This routine makes it possible to evaluate and compare various oil producing units and also existing plants that have similar structure and operate under similar conditions. The methodology was applied to evaluate the exergy efficiency of an oil production unit during its design phase. The following results were found:

$$\varepsilon = 12\%;\ \chi_{\text{Aux}} = 6\%;\ \chi_{\dot{E}_{L+D}} = 82\%$$

for the designed unit, and:

$$\varepsilon = 25\%;\ \chi_{\text{Aux}} = 13\%;\ \chi_{\dot{E}_{L+D}} = 62\% \,,$$

to the feasible reference model of the same unit.

8. DISCUSSIONS AND CONCLUSIONS

More than a quantitative evaluation of the performance of a process unit, the exergetic analysis allows a qualitative identification of the energy degradation of each one of the performed processes. Using the concept of exergy, a methodology was developed to calculate the exergetic performance of stationary oil and gas producing units. The methodology can be applied at the design level of these units as well as to asset the performance of operating ones. As part of the methodology, the procedure is applied also to establish the expected performance of a reference unit, which is defined as the one that corresponds to the most updated available technology. In order to maintain a certain degree of generality, some specific conditions of real arrangements were not considered. Therefore, the structural arrangement and the operational conditions of the real or of the still in design unit shall be strictly replicated in the reference unit.

The methodology can be used from the start point of the design project of a unit. In this way, the exergetic efficiency can be used as a powerful instrument in setting up subsequent and more complete arrangements in each phase of the project. In each of these phases, the performance of alternative arrangements can also be evaluated.

The results of the previous section show that it is possible to increase the exergetic efficiency of the production units, specially supplying the energetic demands with the existing sources and also with the use of more efficient equipment.

Finally, it must be remarked that is also possible to extend the proposed methodology, completing it with an economical evaluation of the producing unit, specifically with the costs associated with the calculated exergy fluxes.

9. REFERENCES

Ghiorzi, T.M., 1997, "Análise Exergética em Plantas de Separação Primária de Petróleo". (M.Sc. Dissertation), Campinas, Brazil, XIII, 100p.

Neves, M.V.S., 2008, "Exergetic Efficiency for Stationary Oil Producing Units", COPPE / UFRJ (M.Sc. Dissertation), Rio de Janeiro, Brazil, XVI, 152p.

Szargut, J., Morris, D.R., Steward, F.R., 1988, "Exergy analysis of thermal, chemical, and metallurgical processes", New York/Berlin, Hemispere/Springer.

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