

EXERGETIC ANALYSIS APPLIED IN THE PRIMARY PROCESSING IN OFFSHORE FIELDS

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Abstract. *In the petroleum production is extracted a mixture of water, gas, oil and also impurities; so it is necessary to process this mixture in order to remove all the economically attractive phases, as oil and gas, as well as extracting water and impurities. This three-phase separation process of oil and gas is done in offshore fields with the use of various pieces of equipment such as biphasic separator, three-phase separators, hydrocyclones, electrostatics separators and centrifuges. This separation process, besides having an economic interest in oil phase, present also a great interest with respect to gas phase, since the combination of the gas with the water creates hydrates, which can difficult the transport through the ducts, and difficulty the posterior refining of oil remaining. The primary processing requires units with a large numbers of pieces of equipment with high energy consumption, and that still generate, large amounts of water for disposal depending of the characteristics of them. This water to be discarded have to be within quality standards pre-defined by the environmental issues, so, its treatment provides an important step in the primary processing due to high levels of oil and impurities in the water. Aiming to analyze the problem of the high energy consumption from the piece of equipment, to optimize the use of piece of equipment and their layout, can be used the exergetic analysis theory, that permit quantify the process lost, their economic costs and also, the generation of irreversibility that impacts the environment. With this concept it is possible to analyze the behavior of each stage of primary processing, pointing out its efficiency with respect to plants in general and, through an arrangement of these data, find a better arrangement or advanced technologies with respect to the effectiveness of processing. The present work computed a exergetic analyze to the primary process of oil separation in offshore platforms*

Keywords: *Oil, Primary Processing, Exergy, Exergetic Analysis*

1. INTRODUCTION

Oil is a mixture of hydrocarbons and other elements such oxygen, sulphur, nitrogen and heavy metals, its concentration varies from one oil field to another (Santos, 2007). The contaminants, that are considered impurities, can be found throughout the distillation range of oil, tending to concentrate as heavy fractions. In the petroleum extraction process of an offshore field is common the production of oil, natural gas, water and impurities. According to the well morphology, such as rock type and the oil properties, the water and impurities quantities can vary.

Over the years, the quantity of water produced in oil well tends to be higher, and several factors must be taken into account in its management. This water may be in the oil well since its formation process, or it was resulted from water injection. So, the primary processing of oil has the aim to separate the economically attractive plots, such as oil and gas, from water and impurities that could damage the process systems and the petroleum refining.

There are two basic types of oil: the first one is called conventional or light oil, and the other one is known as non-conventional or heavy oil. Recently, the participation of heavy oil in the world's production had a massive increase, while the share of medium and light oil suffered a significant decline. So, the primary processing will be subordinated to the petroleum type, requiring the adequacy according to the characteristics of the processed oil.

2. EXERGETIC ANALYSIS OF THE FPSO OPERATING IN SIRI WELL

The First Law of Thermodynamics enounces that the energy can change from many states to others, but it is never lost, (Sotomonte, 2009). Unlike the energy, the exergy doesn't satisfy the conservation law, i.e., all the irreversible process in the nature causes an irrecoverable loss of exergy (Szargut, 2005).

The Siri Member Reservoir, well named as 9-BD-18HP-RJS (Petrobras, 2007), situated in Campos Basin, Rio de Janeiro, Brazil, with capacity to produce 12.5° API heavy oil, requiring a special attention for the primary process to separate the phases, which is different if compared to the conventional oil primary process. Figure 1 illustrates the primary processing plant of Siri field.

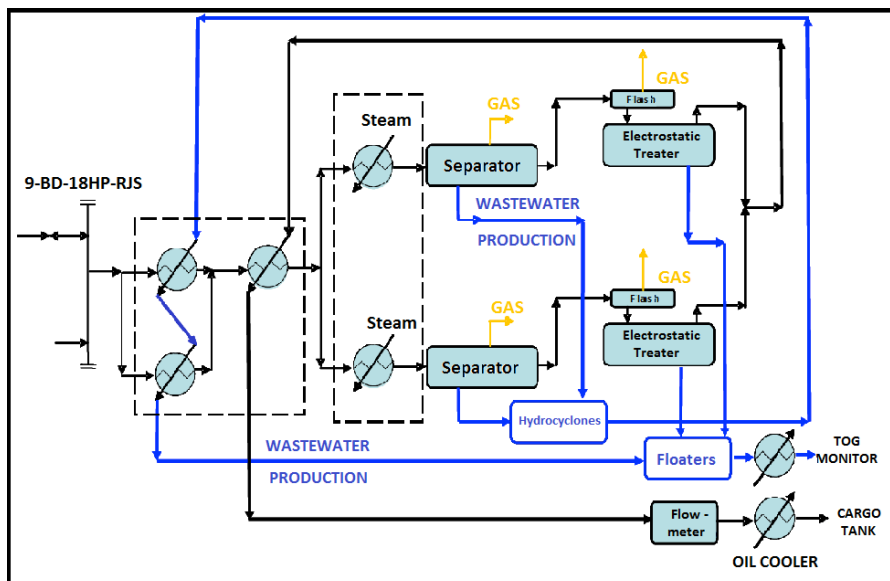


Figure 1. Diagram of the separation and processing of oil (Petrobras, 2007)

However, to calculate the exergy of each equipment in the platform of Siri field, some considerations and simplifications were made. Figure 2 shows the simplifications made, using them as a basis for calculations. The main operation data are shown in Tab. 1.

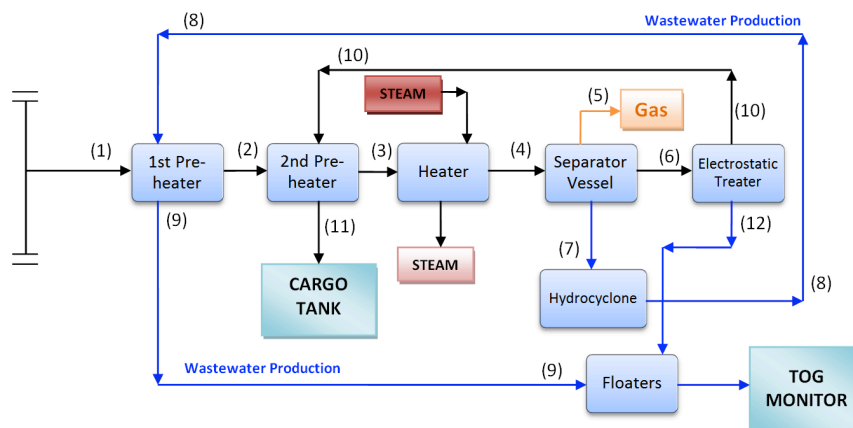


Figure 2. Simplified diagram of the process of separation and treatment of oil from the Siri Platform

Table 1. Main operating data from the operation plant

Equipment	Operation temperature		Operation Pressure (kgf/cm ²)
	Input (°C)	Output (°C)	
1° Pre-heater	40	65	12
2° Pre-heater	65	95	11
Heater	95	130	10
Separation Vessel	130	125	10
Eletrostatic Treater	125	120	4,5

3. ANALYSIS PROCEDURES AND RESULTS

The exergy analysis may be done using some equations. According to The Exergy Method of Thermal Plant Analysis (Kotas, 1985), the total exergy may be calculated by Eq. (1), which B_g is the total exergy in (kJ/s); n_m is the mixture molar number in (kmol/s); T and T_0 are, respectively, the process temperature in (K) and the reference temperature (298.15K); v is the substance specific volume in (m³/kg); m is the substance incoming flow in (kg/s); P

is the pressure of the process in (kPa) and P_0 is the reference pressure (101.3 kPa); b_m^o is the mixture chemical exergy in (kJ/kmol), calculated by the Eq (2); and $C_{P_k}^b$ is the heat capacity of each substance in (kJ/kmol.K), calculated by the Eq. (3).

$$B_g = n_m \cdot b_m^o + (T - T_0) \cdot \sum_k (n_k \cdot C_{P_k}^b) + v \cdot m (P - P_0) \quad (1)$$

The mixture chemical exergy may be calculated by Eq. (2), which y_k is the substance molar fraction (adimensional); b_k^o is the standard chemical exergy in (kJ/kmol); and R is the universal gas constant in (kJ/kmol.K).

$$b_m^o = \sum_k (y_k \cdot b_k^o) + R \cdot T_o \cdot \sum_k (y_k \cdot \ln y_k) \quad (2)$$

The Equation (3) calculates the heat capacity of each substance, which $h - h_0$ and $s - s_0$ are, respectively, the enthalpy and entropy variations, calculated by Eq. (4) and Eq. (5).

$$C_{P_k}^b = \frac{1}{T - T_o} [(h - h_0) - T_o \cdot (s - s_o)] \quad (3)$$

The enthalpy and entropy variations may be calculated by Eq. (4) and Eq. (5), respectively.

$$h - h_0 = \int_{T_0}^T (C_1 + C_2 \cdot T + C_3 \cdot T^2 + C_4 \cdot T^3 + C_5 \cdot T^4) \cdot dT \quad (4)$$

$$s - s_0 = \int_{T_0}^T (C_1 + C_2 \cdot T + C_3 \cdot T^2 + C_4 \cdot T^3 + C_5 \cdot T^4) \cdot \frac{dT}{T} \quad (5)$$

The constants C_1, C_2, C_3, C_4, C_5 were taken from Handbook of Thermodynamics (Yaws, 1996). Table 2 exemplifies the previous constants for some substance.

The exergy analysis was performed according to the steps of the work development. First, it was calculated the enthalpy and entropy of all substances in the oil, using for this, the constants for the equation of heat capacity, presented in the Handbook of Thermodynamics (Yaws, 1996).

After calculating each enthalpy and entropy, the results were compared with theoretical values (Sandler, 1986), to thus conclude that the calculated values were reliable and useful for the analysis. With this, it were calculated the enthalpies and entropies for all components of the input stream.

Then, it was considered that the density of the oil was approximately equal to the water, because it is heavy oil, and from this, it was calculated the molar fraction of each component, shown in Tab. 3.

For the result, it was needed the standard chemical exergy of each component, and in literature the chemical exergy of C_{16+} are not calculated. Knowing this, it was used a mechanism for calculating the components standard chemical exergy already known and compared with literature values, noting that the standard exergy were very close to the literature (Szagurt, 2005 and Kotas, 1985). This procedure was used to calculate the chemical exergy for unknown substances.

To obtain the chemical exergy, it was calculated a β constant, that multiplied by the enthalpy of combustion results in the standard chemical exergy of the substance. The β constant can be calculated by Eq. (6).

$$\beta = 1.0412 + 0.1728 \frac{z_{H_2}}{z_C} \quad (6)$$

Which, z_{H_2} and z_C are mass fraction of H_2 and C, respectively. Each substance in the feed stream has a β itself, because for each substance the mass of Hydrogen and Carbon varies. Thereafter, this constant was multiplied by the enthalpy of combustion, also characteristic of each component, giving the value of the standard chemical exergy.

Table 2. Constants used to calculate the heat capacity (Yaws, 1996)

Substance	Formula	C ₁	C ₂	C ₃	C ₄	C ₅
Methane	CH ₄	34.942	- 3.9957.10 ⁻²	1.9184.10 ⁻⁴	- 1.5303.10 ⁻⁷	3.9321.10 ⁻¹¹
Ethane	C ₂ H ₆	28.146	4.3447.10 ⁻²	1.8946.10 ⁻⁴	- 1.9082.10 ⁻⁷	5.3349.10 ⁻¹¹
Propane	C ₃ H ₈	28.277	1.1600.10 ⁻¹	1.9597.10 ⁻⁴	- 2.3271.10 ⁻⁷	6.8669.10 ⁻¹¹
i-Butane	C ₄ H ₁₀	6.772	3.4147.10 ⁻¹	-1.0271.10 ⁻⁴	-3.6849.10 ⁻⁸	2.0429.10 ⁻¹¹
n-Butane	C ₄ H ₁₀	20.056	2.8153.10 ⁻¹	- 1.3143.10 ⁻⁵	- 9.4571.10 ⁻⁸	3.4149.10 ⁻¹¹
i-Pentane	C ₅ H ₁₂	-0.881	4.7498.10 ⁻¹	-2.4797.10 ⁻⁴	6.7512.10 ⁻⁸	-8.5343.10 ⁻¹²
n-Pentane	C ₅ H ₁₂	26.671	3.2324.10 ⁻¹	4.2820.10 ⁻⁵	- 1.6639.10 ⁻⁷	5.6036.10 ⁻¹¹
Hexane	C ₆ H ₁₄	25.924	4.1927.10 ⁻¹	- 1.2491.10 ⁻⁵	- 1.5916.10 ⁻⁷	5.8784.10 ⁻¹¹
Heptane	C ₇ H ₁₆	26.984	5.0387.10 ⁻¹	- 4.4748.10 ⁻⁵	- 1.6835.10 ⁻⁷	6.5183.10 ⁻¹¹
Octane	C ₈ H ₁₈	29.053	5.8016.10 ⁻¹	- 5.7103.10 ⁻⁵	- 1.9548.10 ⁻⁷	7.6614.10 ⁻¹¹
Nonane	C ₉ H ₂₀	29.687	6.6821.10 ⁻¹	- 9.6492.10 ⁻⁵	- 2.0014.10 ⁻⁷	8.2200.10 ⁻¹¹
Decane	C ₁₀ H ₂₂	31.780	7.4489.10 ⁻¹	- 1.0945.10 ⁻⁴	- 2.2668.10 ⁻⁷	9.3458.10 ⁻¹¹
Undecane	C ₁₁ H ₂₄	125.212	3.1401.10 ⁻¹	7.9137.10 ⁻⁴	- 9.1410.10 ⁻⁷	2.7568.10 ⁻¹⁰
Dodecane	C ₁₂ H ₂₆	71.498	7.2559.10 ⁻¹	1.1553.10 ⁻⁴	- 4.1196.10 ⁻⁷	1.4141.10 ⁻¹⁰
Tridecane	C ₁₃ H ₂₈	110.400	5.3321.10 ⁻¹	7.3984.10 ⁻⁴	- 1.0212.10 ⁻⁶	3.2423.10 ⁻¹⁰
Tetradecane	C ₁₄ H ₃₀	115.502	6.0882.10 ⁻¹	6.8043.10 ⁻⁴	- 9.7091.10 ⁻⁷	3.0756.10 ⁻¹⁰
Pentadecane	C ₁₅ H ₃₂	124.647	6.2706.10 ⁻¹	8.3164.10 ⁻⁴	- 1.1689.10 ⁻⁶	3.7326.10 ⁻¹⁰
Hexadecane	C ₁₆ H ₃₄	131.750	6.7397.10 ⁻¹	8.7770.10 ⁻⁴	- 1.2430.10 ⁻⁶	3.9785.10 ⁻¹⁰
Heptadecane	C ₁₇ H ₃₆	111.903	9.5987.10 ⁻¹	2.7901.10 ⁻⁴	-6.7520.10 ⁻⁷	2.2545.10 ⁻¹⁰
Octadecane	C ₁₈ H ₃₈	124.715	9.8653.10 ⁻¹	3.4273.10 ⁻⁴	-7.4838.10 ⁻⁷	2.4804.10 ⁻¹⁰
Nonadecane	C ₁₉ H ₄₀	132.530	1.0358	3.6926.10 ⁻⁴	-7.9581.10 ⁻⁷	2.4804.10 ⁻¹⁰
Eicosane	C ₂₀ H ₄₂	137.730	1.0992	3.6839.10 ⁻⁴	-8.2058.10 ⁻⁷	2.7259.10 ⁻¹⁰
Water	H ₂ O	33.933	- 8.4186.10 ⁻³	2.9906.10 ⁻⁵	- 1.7825.10 ⁻⁸	3.6934.10 ⁻¹²
Nitrogen	N ₂	29.414	- 4.5993.10 ⁻³	1.3004.10 ⁻⁵	- 5.4759.10 ⁻⁹	2.9239.10 ⁻¹³
Carbon Dioxide	CO ₂	27.437	4.2315.10 ⁻²	- 1.9555.10 ⁻⁵	3.9968.10 ⁻⁹	- 2.9872.10 ⁻¹³

Table 3. Molar flows of the primary processing plant

Substance	Phase	Flows 1-4 kmol/s	Flow 5 kmol/s	Flow 6 kmol/s	Flow 7 kmol/s	Flow 10 kmol/s	Flow 12 kmol/s
CO ₂	g	0.00989	0.00989	-	-	-	-
N ₂	g	0.00015	0.00015	-	-	-	-
CH ₄	g	0.03351	0.03351	-	-	-	-
C ₂ H ₆	g	0.00046	0.00046	-	-	-	-
C ₃ H ₈	g	0.00017	0.00017	-	-	-	-
iC ₄ H ₁₀	g	0	0	-	-	-	-
nC ₄ H ₁₀	g	0.00015	0.00015	-	-	-	-
iC ₅ H ₁₂	g	2.89E-05	2.896E-05	-	-	-	-
nC ₅ H ₁₂	g	5.78E-05	5.781E-05	-	-	-	-
C ₆ H ₁₄	g	5.78E-05	5.781E-05	-	-	-	-
C ₇ H ₁₆	l	1.45E-05	-	1.44E-05	1.414E-08	1.44E-05	-
C ₈ H ₁₈	l	1.45E-05	-	1.44E-05	1.414E-08	1.44E-05	-
C ₉ H ₂₀	l	2.89E-05	-	2.89E-05	2.827E-08	2.89E-05	-
C ₁₀ H ₂₂	l	0.00042	-	0.00042	4.099E-07	0.00042	-
C ₁₁ H ₂₄	l	0.00106	-	0.00105	1.032E-06	0.00106	-
C ₁₂ H ₂₆	l	0.00152	-	0.00152	1.484E-06	0.00152	-
C ₁₃ H ₂₈	l	0.00249	-	0.00248	2.431E-06	0.00248	-
C ₁₄ H ₃₀	l	0.00289	-	0.00289	2.827E-06	0.00289	-
C ₁₅ H ₃₂	l	0.00382	-	0.00381	3.731E-06	0.00381	-
C ₁₆ H ₃₄	l	0.00283	-	0.00283	2.770E-06	0.00283	-
C ₁₇ H ₃₆	l	0.00263	-	0.00263	2.572E-06	0.00263	-
C ₁₈ H ₃₈	l	0.00312	-	0.00312	3.0529E-06	0.00312	-
C ₁₉ H ₄₀	l	0.00234	-	0.00234	2.2897E-06	0.00234	-
C ₂₀ H ₄₂	l	0.07691	-	0.07684	7.522E-05	0.07684	-
H ₂ O	l	0.83096	-	0.10397	0.726995	0.00052	0.10345

It was considered that 35% of the inflow was water. With the mass fractions taken from Petrobras (2007), and molecular weights of each substance, it was calculated the mass flow of oil, excluding water. By proportion, it was considered that the total oil corresponds 65% of the total mass input, so the mass of water was obtained. Adding the mass of water and oil, it was found the total mass of the input stream.

The oil processing capacity is 2400 (m³/day) (Petrobras, 2007), was transformed in (kg/s) from the consideration that the density of oil is close to water. Dividing this capacity in (kg/s) by the total mass of oil, it was obtained the processing capacity in (kmol/s). With this value, it was multiplied by each weight fraction of oil, finding the quantity in (kmol/s) of each substance present in the stream.

The mole fraction of each component was calculated from the division of its value in (kmol/s) by the total value at (kmol/s). The mol fraction remains constant from the Flow (1) until Flow (4). After passing the separator, the molar fractions are as follows: Flow (5) - gases mole fraction; Flow (6) - molar fraction with 99.9% of initial oil and 7% of initial water; Flow (7) - molar fraction with 0, 1% of initial oil (2000 ppm) and 93% of initial water; Flow (10) – with 100% of the Flow (6) oil and 0.5% of that water; Flow (12) - 99.5% of the Flow (6) water.

With the standard chemical exergy values of each component, the molar fractions and considering the reference temperature, as the ambient temperature of 25 °C, it was calculated chemical exergy of the mixture flows, using (2).

Using the enthalpies and entropies calculated in the beginning for each considered temperature, it was used (7) to calculate the exergy of the mixture flows, whose calculated values are presented in Table (4).

After passing through the hydrocyclone, the water flow (8) is used as a heat source to heat the mixture passing through the first pre-heater. From the heat balance using the first law of thermodynamics, it was calculated the enthalpy of the water after passing through the first pre-heater. Thus, the final temperature of the water after passing through this equipment (Flow 9) is about 43°C.

The separated oil in the process, Flow (10), is also used for heating the mixture in the second pre-heater. Thus, from the same procedure described previously, it was calculated the final temperature after the passage of this oil in preheater (Flow 11), and obtained a value of 72°C. From these temperatures, it may calculate the exergy of these two flows, as shown in Tab. 4. However, the third heat exchanger which operates with saturated steam at 184°C and pressure of 11 bars at the entrance, it was not possible to evaluate its exergy efficiency for lack of more data. Moreover, also for lack of data was not calculated exergy efficiency of the electrostatic treater.

Table 4. Exergy Flows

Flow 1 (B ₁) (kW)	Flow 2 (B ₂) (kW)	Flow 3 (B ₃) (kW)	Flow 4 (B ₄) (kW)	Flow 5 (B ₅) (kW)	Flow 6 (B ₆) (kW)
1288906.0	1289136.6	1289676.0	1290620.8	31674.0	1256930.7

Flow 7 (B ₇) (kW)	Flow 8 (B ₈) (kW)	Flow 9 (B ₉) (kW)	Flow 10 (B ₁₀) (kW)	Flow 11 (B ₁₁) (kW)	Flow 12 (B ₁₂) (kW)
2743.92	1627.4	1299.6	1256988.9	1256263.4	70.1

To calculate the exergy transferred by each pre-heater and heater to the incoming flow, it was used the Eq. (7), Eq. (8) and Eq. (9) to the first and second pre-heater, and also the heater, respectively. The transferred exergies values are exposed in Tab. 5, using the exergy values exposed in Tab. 4.

$$B_{1st} = B_2 - B_1 \quad (7)$$

$$B_{2nd} = B_3 - B_2 \quad (8)$$

$$B_{heater} = B_4 - B_3 \quad (9)$$

Table 5. Transferred exergy to the water-oil mixture in the heaters

1° Pre-heater (kW)	2° Pre-heater (kW)	Heater (kW)
230.6	539.4	944.8

The exergetic efficiency of the first and second pre-heater can be calculated by the Eq. (10) and Eq. (11), respectively. The calculated efficiency is shown at Tab. 6.

$$\eta_{1st} = \frac{B_2 - B_1}{B_8 - B_9} \quad (10)$$

$$\eta_{2nd} = \frac{B_3 - B_2}{B_{10} - B_{11}} \quad (11)$$

To calculate the hydrocyclone efficiency it was used the capacity of the equipment in separating the oil from the water. Through the exergy values of each flow, it was found the exergy of the separated oil doing the difference between the inflow and outflow exergy values. With the separated oil value, subtracted from the incoming flow exergy, it has the exergy of the water and the remaining oil after passing the hydrocyclone. Thus, the ratio between the outlet water exergy and inlet flow exergy in the equipment shows the hydrocyclone efficiency, presented in Eq. (12).

$$\eta_{hydro} = \frac{B_7 - (B_7 - B_8)}{B_7} = \frac{B_8}{B_7} \quad (12)$$

The hydrocyclone efficiency value is also available in Tab. 6.

Table 6. Exergetic Efficiency

1° Pre-heater (%)	2° Pre-heater (%)	Hydrocyclone (%)
70.35	74.35	59.5

4. CONCLUSION

In a primary processing facility the big need of energy in various equipments that composes the plant, when confronted with the values now involved in exergy analysis, reveal many interesting information because of the large chemical exergy of flows present in oil.

The increase of exergy of the separator feed flow in a water-in-oil emulsion with 35% water, necessary to reach the operating temperatures of the three-phase separator, 130°C, requires a full transfer of approximately 1715 kW. About 45% of the exergy necessary to the process comes from the heat recovered from water and oil flows, and must have their temperature reduced for disposal in the case of water, either for the oil storage in the cargo tank.

Thus, can be concluded by the results of the pre-heater and heater energy consumption, that the energy required for primary processing to occurs is relevant and that this analysis is of extreme importance for the company, as well as the exergetic efficiency values of equipment that are able to avoid the excessive cost to this.

It's worth noting that from the exergy viewpoint, the exergy transferred to emulsion feed if compared to the chemical exergy in the gravity separator, represents only 1.3% of this total. This means that considered the process losses the energy consumption directly related to the process is small. Thus, considering the costs of the final product on the market, solutions for the exploitation of heavy oil reserves are becoming attractive.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

- Kotas, T.J., 1985. The exergy method of thermal plant analysis. Butterworths, London.
- Petrobrás, 2007. Production activity to Siri Member reservoir research, in Badejo concession, Campos Basin. Technical Report: EDQ 0206/07, Rio de Janeiro.
- Sandler, S.I., 1989. Chemical and Engineering Thermodynamics. John Wiley & Sons, Singapore.
- Santos, A.R., 2007. A Geração de coque de petróleo devido ao processamento de petróleo pesados e o seu uso na produção de clínquer de cimento Portland. Ph.D. thesis, Federal University of Itajubá, Itajubá, MG, Brazil.
- Sotomonte, C. A. R., 2009. Análise Exergética, Termoeconômica e Ambiental de uma Usina Termoeletrica Supercritica a Carvão Mineral. Dissertation in Mechanical Engineering, Federal University of Itajubá, Itajubá, MG, Brazil.

- Szargut, J., 2005. Exergy method – technical and ecological applications. Series: Developments in Heat Transfer, vol. 18. WITPress.
- Yaws, C.L., 1996. Handbook of Thermodynamic diagrams. Gulf Publishing Company, Houston, Texas, United States of America.

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