

ENC-2022-0032

COMPARATIVE THERMOECONOMIC RESULTS ANALYZING A BRAYTON – REFRIGERATION CYCLE

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Abstract. *This work aims at the thermoeconomic analysis of the cogeneration system that uses a Brayton cycle turbine and R134a gas vapor compression refrigeration system to produce 3 MW of electricity and 10 TR, using natural gas as fuel. The objective of the analysis is to obtain the unit exergetic costs of the cogeneration system, from the application of different thermoeconomic models: SPECOC, E, E&S, H&S, UFS and UFS+. To achieve this purpose, system simulation and evaluation of thermoeconomic models were developed using the Engineering Equation Solver (EES) software to simulate the unit exergetic costs (k^*) of cogeneration. The results indicated that the unit exergetic costs of the products of the cogeneration cycle electrical power and evaporator heat were equal to 2.75 kW/kW and 5.34 kW/kW, in the analyzes carried out from the all the models under study. It was observed that the higher the level of exergy disaggregation by a model proposed, the higher the level of complexity presented.*

Keywords: *Thermoeconomic, Exergetic Cost, Exergy, Cogeneration, Applied Thermodynamics.*

1. INTRODUCTION

The projections on global energy demand, based on economic development and population growth worldwide, point to the growth of world energy consumption, as well as the generation of electric energy, a great amount of the world energy demand, remains the bottleneck in terms of emission of gases causing climate change from global warming. Kharseh et al. (2011) state that the analyzes carried out on the temperature clearly confirm that there is a change on a continental scale in the air temperature of the Earth's surface. Studies on the temporal advance of temperature show that it increased by 1.4 °C from 1880 to 2008. Therefore, it is extremely important that energy generation processes are more efficient, combining technological advances and studies on energy efficiency with good energy saving practices.

According to Torres et al. (2007), in thermodynamic analysis, the study is generally focused on describing the processes and relationships between mass flows and energy exchanges. The analysis of energy systems based on the second law of thermodynamics is called exergetic analysis. Kwak et al (2003) highlighted the importance of the concept of exergy, understood as the maximum useful work that can be obtained from a matter or energy flow. The main objective of exergetic analysis is to determine the location and amount of irreversibility of a system.

Sahoo (2008) defines thermoeconomic as the branch of engineering that combines exergetic analysis with economic constraints to provide the system designer with information not available through conventional energy analysis and economic evaluation. Tsatsaronis and Moran (1997) show that the objectives of thermoeconomic analysis can be: (a) separately calculate the cost of each product generated by a system with more than one product; (b) understand the cost formation process in the system; (c) optimize specific variables in a single component; or (d) optimize the system in general.

Over the years, several thermoeconomic methodologies have been developed, each one with its particularities and limitations, so this work aims to present the thermoeconomic analysis of a cogeneration system that uses a Brayton cycle turbine and a vapor compression refrigeration system, from different thermoeconomic models: SPECOC, E, E&S, H&S, UFS and UFS+, in order to obtain and compare the unit exergetic costs of the cogeneration system, the strengths and limitations of the different thermoeconomic models applied to the cogeneration cycle under study.

2. METHODOLOGY

To achieve the objective of this study, that is, to obtain and compare the unit exergetic costs, from the application of different thermo-economic models: SPEC0, E, E&S, H&S, UFS and UFS+, a cogeneration cycle with a Brayton turbine and a vapor compression refrigeration system was used as a basis, Figure 1. The cycle consists of two systems, the first one, which is a Brayton gas power cycle, consists of a compressor (C_1), combustion chamber (CC) and gas turbine (T_g). This system operates using natural gas as fuel at a flow rate of 0.167 kg/s and lower calorific value equal to 49,742 kJ/kg, to produce 3.1 MW of energy liquids. Other data were considered for the evaluation of this system, thus, compression ratio and air/fuel ratio equal to 12 and 30, respectively; isentropic turbine and compressor efficiency equal to 88 % and 83 %, respectively.

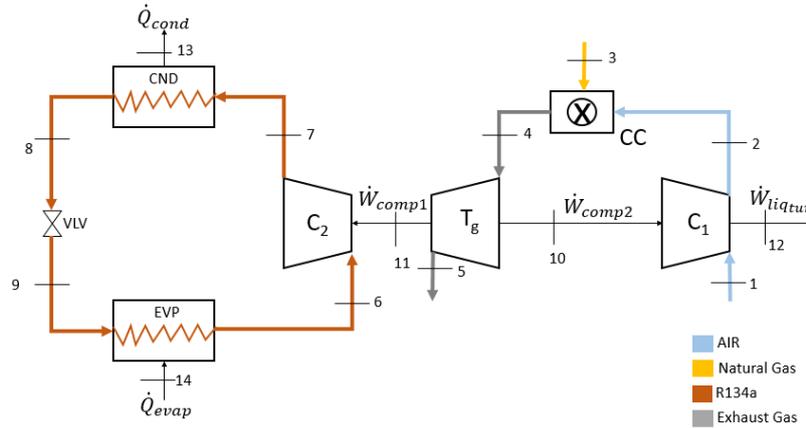


Figure 1. Brayton – Refrigeration Cycle

The second system is a refrigeration cycle by compression of the gas R134a, which is connected to a cold region at 0° C by the evaporator and a hot region, the external environment (Temperature, $T_0=26$ °C and Pressure, $P_0=101.3$ kPa). The working fluid has a mass flow rate of 0.233 kg/s and is compressed in the compressor (C_2), which has an exergetic efficiency of 80 %. C_2 consumes 9.09 kW of energy while the evaporator (EVP) takes 35.17 kW from the cold environment, so the system has a thermal load of 10 TR. In addition to these equipment, the refrigeration cycle has a pressure expansion valve (VLV) and condenser (CND). The energetic and exergetic analyzes and the thermo-economic balances were performed using EES software. Table 1 presents the thermodynamic data of the cogeneration cycle in question. The thermo-economic models applied in this study will be presented.

Table 1. Thermodynamic data of the cogeneration system

| Flow (i) | m(kg/s) | T (°C) | P (kPa) | h (kJ/kg) | s (kJ/kg.K) | u (kJ/kg) | v (m ³ /kg) |
|----------|---------|--------|---------|-----------|-------------|-----------|------------------------|
| 1 | 5.000 | 25.0 | 101.3 | 298.6 | 5.6950 | 213.00 | 0.8446 |
| 2 | 5.000 | 394.2 | 1216.0 | 678.7 | 5.8080 | 487.10 | 0.1575 |
| 3 | 0.167 | 15.0 | 3447.0 | -4482.0 | 9.3700 | -4624.00 | 0.0412 |
| 4 | 5.167 | 1696.0 | 1192.0 | 346.4 | 8.4160 | -235.00 | 0.4878 |
| 5 | 5.167 | 973.4 | 101.3 | -630.6 | 8.5270 | -998.70 | 3.6320 |
| 6 | 0.233 | -10.0 | 200.7 | 244.5 | 0.9377 | 224.50 | 0.0995 |
| 7 | 0.233 | 48.8 | 900.0 | 283.5 | 0.9622 | 261.30 | 0.0246 |
| 8 | 0.233 | 30.0 | 900.0 | 93.6 | 0.3475 | 92.82 | 0.0008 |
| 9 | 0.233 | -10.0 | 200.7 | 93.6 | 0.3641 | 88.13 | 0.0271 |

2.1 SPEC0 Method

According to Lourenço (2016), the application of the SPEC0 method occurs through three steps, the first is the exergetic analysis of the system, followed by the definition of fuel and product of each component, and, finally, the application of equations of exergoeconomic cost balance. The exergy of a flow (i) can be calculated by adding its physical (B_f) and chemical portions. The physical portion of exergy is calculated according to Eq. (1), and in this work the chemical exergy was calculated as proposed by Lozano and Valero (1986).

$$B_f = m_i [(h_i - h_0) - T_0(s_i - s_0)] \quad (1)$$

In “Equation 1”, the indexes *i* and 0 refer to the state under analysis and the conditions of the reference environment. Lourenço (2016) points out that the product in the SPECO method is defined as all exergy flows leaving the component and the addition of exergy of a respective mass flow, which is in accordance with the component's purpose. Otherwise, the fuel is defined as all exergy flows that enter the component plus all exergy decreases between a flow that enters and leaves the component. Due to the definitions of fuel and product of this methodology, it is not possible to define an product for the dissipative components, CND and VLV; at the authors' discretion, these components were added to the compressor, thus making them the C₂-CND-VLV production unit, as shown in Fig. 2-A. Table 2 shows the definition of fuel and product for the cogeneration cycle, according to the method in question.

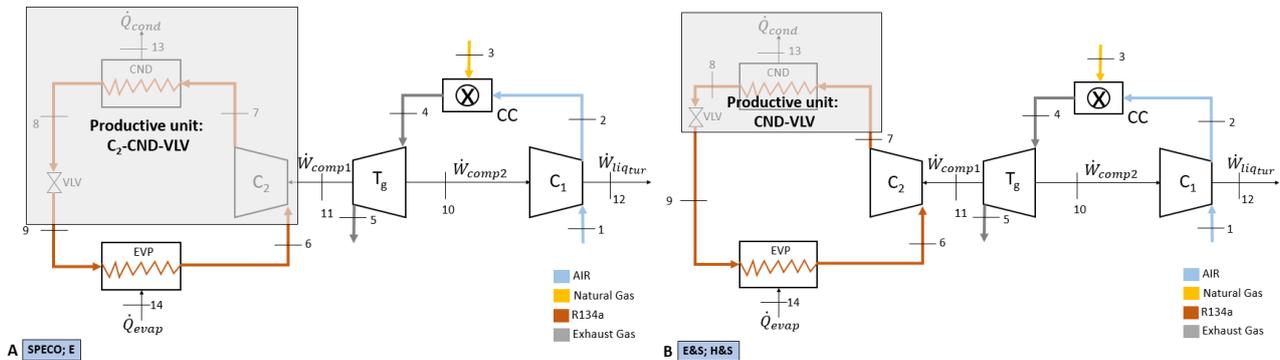


Figure 2. Physical structure considered in the models: a) SPECO and E b) E&S and H&S

Table 2. Fuel and products of each component according to the SPECO method and E Model

| SPECO | | | E Model | | |
|-------------------------|--------------------------------|---|-------------------------|------------------|-----------------------|
| Component | Fuel | Product | Component | Fuel | Product |
| C ₁ | B ₁₀ | B ₂ -B ₁ | C ₁ | B ₁₀ | B _{2;1} |
| CC | B ₃ | B ₄ -B ₂ | CC | B ₃ | B _{4;2,5} |
| T _g | B ₄ -B ₅ | B ₁₁ +B ₁₀ +B ₁₂ | T _g | B _{4;5} | B _{11,10,12} |
| C ₂ -CND-VLV | B ₁₁ | B ₉ -B ₆ | C ₂ -CND-VLV | B ₁₁ | B _{9;6} |
| EVP | B ₉ -B ₆ | B ₁₄ | EVP | B _{9;6} | B ₁₄ |

To calculate the unit exergetic cost (k^*) of each flow in the system, the mathematical model of cost allocation is used, which is a set of cost equations obtained from the thermoeconomic balance in each component of the cycle, according to Eq. (2). The solution of this set of equations portrays the unit exergetic costs of each flow that enter (in) or leave (out) the components. The unit exergy cost of a flow (kW/kW) is the amount of exergy required to obtain one unit of exergy from that flow. This cost is a measure of the thermodynamic efficiency of the production process that generates this flow.

$$\sum k_{out}^* \cdot Y_{out} - \sum k_{in}^* \cdot Y_{in} = 0 \quad (2)$$

In Equation 2, k_{out}^* and k_{in}^* are unknown variables that represent the unit exergetic cost of the component's output and input flows, respectively; Y_{out} and Y_{in} represent the generic flow (in kW) at the inlet and outlet of the components, respectively, which can be evaluated using any thermodynamic magnitude, such as power (W), total exergy (B), negentropy (S), enthalpy (H), etc. It is important to remark that the equation was set to zero because in this study external fuel consumption was not considered.

According to Dos Santos (2016), as the number of flows is always greater than the number of production units or components, auxiliary equations are necessary. For thermoeconomic models based on physical structure, the criteria for auxiliary equations are the fuel and product principles. According to the fuel principle, a component is considered to use part of the input flow to produce a given product. Thus, the remaining part of the input stream (which is one of the output streams) carries the same unit cost as the input stream. On the other hand, the product principle considers that all outflows have the same unit cost, in addition, the unit exergetic cost of the fuel is considered 1 kW/kW. At the authors' discretion, the allocation of waste costs (flow 5) was made in the combustion chamber, since the heat rejected to the environment is a consequence of the burning of the fuel that takes place inside this equipment.

2.2 E Model

According to Santos (2009), the E model originates from the combination of the concepts of the Exergetic Cost Theory and the SPECO Method, and it is also based on the use of total exergy. However, this model, as well as the next ones presented, is based on the definition of the productive diagram. Lorenzoni (2017) explains that in the productive diagram, the equipment that makes up the cycle are called production units and are represented by rhombus, connected by arrows that represent the flows of fuel and products, in the input and output directions, respectively. In the presence of more than one input stream in a unit, junctions represented by rhombus are used. Likewise, in cases of more than one outflow, bifurcations are used, represented by circles.

As in the SPECO model, it is necessary to define the inputs and products, now based on the production diagram. Again, as it is not possible to define a product for the dissipative equipment, the aggregation of these components in C_2 was considered, as shown in Fig. 2-A. When applying E model in the cogeneration cycle under analysis, the fuel and products of each production unit are defined, according to Tab. 2, while the productive structure can be seen in Fig. 3.

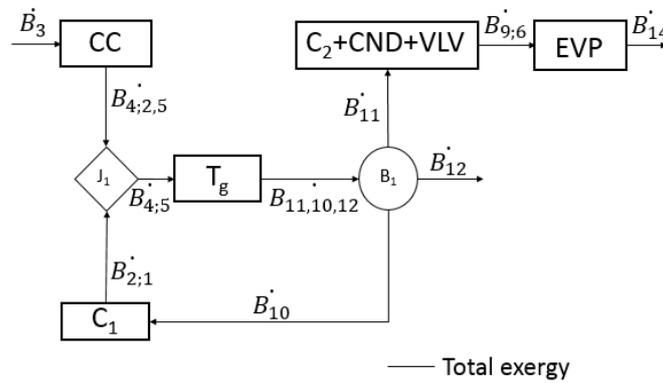


Figure 3. Productive diagram according to E Model

As it can be seen in Tab. 1 and Fig. 3, with the change from the physical structure to the productive diagram, a new nomenclature was adopted, according to the variations of each flow of the productive diagram, based on the indices of the flows of the physical structure, as exemplified in Equation 3.

$$Y_{a,b;c,d} = (Y_a + Y_b) - (Y_c + Y_d) \quad (3)$$

In Equation 3, Y represents the generic flow (in kW) in the productive diagram, and a , b , c and d represent the indexes of the physical structure to which the generic flow it refers. The unit exergetic cost (k^*) of each flow of the production diagram is calculated using the mathematical model of cost allocation, the thermoeconomic balance is performed for each production unit, according to Eq. 2, and the set of equations is completed using the equations associated with each junction and bifurcation. For each junction, an equation is obtained, which is also defined according to the concept presented in Eq. 2. Each bifurcation presents the number of equations according to the number of outputs it has, given that conceptually the outputs of a bifurcation have the same unit exergetic cost as their input.

2.3 E&S Model

Frangopoulos (1983) describes negentropy as a fictitious flow of entropic variation, with the main purpose of defining a product for the condenser in the productive diagram, which allows its disaggregation. Lorenzoni (2017) states that, as it is the first modeling that allows the desegregation of the condenser, this modeling is highly accepted in the current academic environment. The negentropy is calculated by making the entropy negative, this last one calculated according to Eq. 4.

$$S_i = m_i \cdot T_0 (s_i - s_0) \quad (4)$$

In modeling according to the E&S model, in the productive diagram, the total exergy flows are represented, calculated according to the physical and chemical portions of exergy, and the negentropy flows. With this method, the VND is disaggregated, however, it is not possible to define the product for the VLV, so the aggregation of the VLV to the VND will be considered, thus considering, at the authors' discretion, the VND-VLV production unit, as Fig. 2-B.

When applying the E&S model in the cogeneration cycle under analysis, the fuel and products of each production unit are defined, according to Table 3, while the production structure can be seen in Figure 4.

Table 3. Inputs and products of each production unit according to the E&S and H&S Models

| E&S Model | | | H&S Model | | |
|----------------|-------------------------------------|-----------------------|----------------|--|-------------------------------------|
| Component | Fuel | Product | Component | Fuel | Product |
| C ₁ | B ₁₀ + S _{2;1} | B _{2;1} | C ₁ | B ₁₀ + S _{2;1} | H _{2;1} |
| CC | B ₃ + S _{4;2} | B _{4;2} | CC | B ₃ + S _{4;2} + X _{5;1} | H _{4;2} + X _{4;2} |
| T _g | B _{4;5} + S _{5;4} | B _{11,10,12} | T _g | H _{4;5} + S _{5;4} | B _{11,10,12} |
| C ₂ | B ₁₁ + S _{7;6} | B _{7;6} | C ₂ | B ₁₁ + S _{7;6} | H _{7;6} |
| CND-VLV | B _{7;9} | S _{7;9} | CND-VLV | H _{7;9} | S _{7;9} |
| EVP | B _{9;6} + S _{6;9} | B ₁₄ | EVP | S _{6;9} | B ₁₄ + H _{6;9} |
| AMB | B _{5;1} | S _{5;1} | AMB | H _{5;1} + X _{4;2} | S _{5;1} + X _{5;1} |

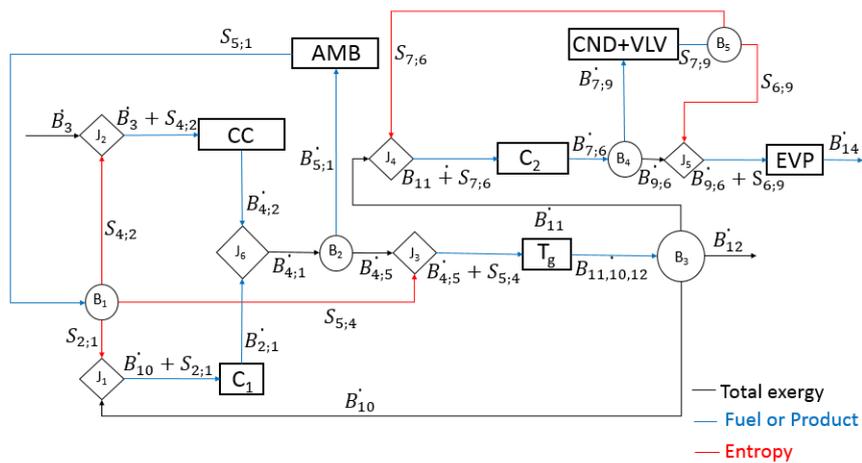


Figure 4. Productive diagram according to E&S Model

In the productive diagram, Fig. 4, the ambient productive unit, AMB, was inserted, which was used to internalize the cost of exhaust gases from the gas turbine cogeneration system. The mathematical model of cost allocation occurs as already evidenced in the previous item.

2.4 H&S Model

The H&S Model, developed by Santos et al. (2006), is based on the disaggregation of total exergy into its enthalpic (H) and entropic (S) portions, which along with (H-S) represent the physical exergy and chemical portion (X). The H and S portions are calculated according to Eq. 5 and Eq. 4, respectively. As mentioned above, chemical exergy was calculated as proposed by Lozano and Valero (1986).

$$H_i = m_i (h_i - h_0) \quad (5)$$

According to Lorenzoni (2017), the entropy flow works in the same way as the negentropy flow, every component that increases the entropy of the system consumes it, while those that decrease it are its producers. The equipment that consumes and produces chemical enthalpy and exergy are defined according to their contributions to the flow, similarly to what happens in the total exergy flows of the previous models. According to the previous model, it is possible to define the input and output for the CND, however, the VLV remains without a defined product and, thus, remains considered aggregated to the CND, as shown in Fig. 2-B.

When applying the H&S model in the cogeneration cycle under analysis, the fuel and products of each production unit are defined, according to Tab. 3, while the productive structure can be seen in Fig. 5. Obtaining unit exergetic costs by applying the mathematical model of cost allocation has already been explicit.

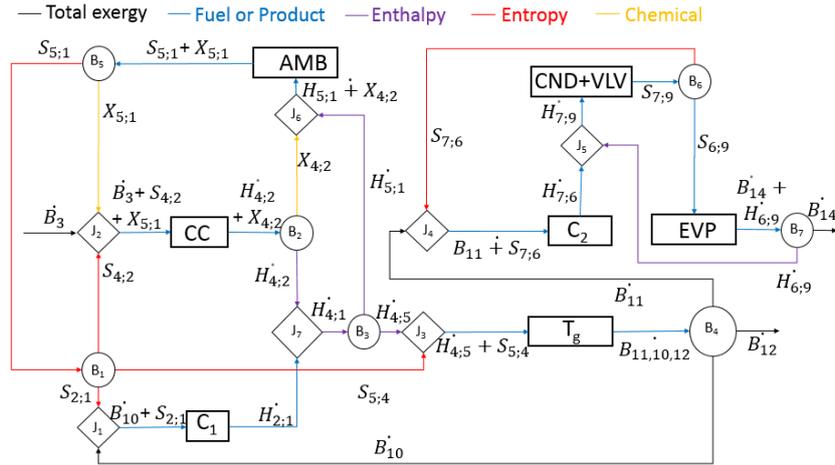


Figure 5. Production diagram according to the H&S model

2.5 UFS Model

In the UFS Model, which was presented by Lourenço (2012), one more level of physical exergy disaggregation is proposed, this time it is considered in terms of its internal energy (U), flow work (F) and the portion entropic (S). The portions U, F and S are calculated according to Eq. 6, Eq. 7 and Eq. 4, respectively.

$$U_i = m_i(u_i - u_0) \quad (6)$$

$$F_i = m_i(P_i v_i - P_0 v_0) \quad (7)$$

As explained by Lorenzoni (2017), the definition of fuel and products of the flows of internal energy and work flow occurs in the same way as the flow of total exergy, while the flow of entropy follows the same principle as negentropy. In this model, it is possible to define input and output for the VLV, which has as a product the variation of internal energy of the fluid in its interior, thus, this is disaggregated from the CND, considering each equipment as a productive unit. When applying the UFS model in the cogeneration cycle under analysis, the fuel and products of each production unit are defined, according to Tab. 4, while the productive structure can be seen in Fig. 6. Obtaining the unit exergetic costs, applying the mathematical model of cost allocation, already explained in item 2.2.

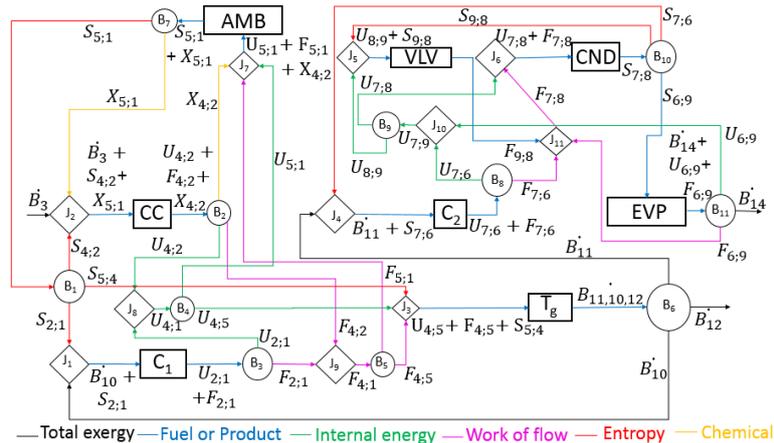


Figure 6. Production diagram according to UFS Model

2.6 UFS+ Model

Developed by Lourenço (2016), this model proposes another level of physical exergy disaggregation, decomposing it into the internal energy (U), volume work (F_v), pressure work (F_p) and entropic portion (S). The portions U, F_v , F_p and S are calculated according to Eq. 6, Eq. 8, Eq. 9 and Eq. 4, respectively.

$$F_{V,i} = m_i P_0 (v_i - v_0) \quad (8)$$

$$F_{P,i} = m_i v_i (P_i - P_0) \quad (9)$$

Lorenzoni (2017) adds that the definitions of fuel and products explicitly follow the same definitions of the UFS model, with flows F_V and F_P considered as fuel when there is a reduction of these in the component and, as product, in the opposite case. In the same way as in the previous model, it is possible to determine output and input for all components of the cycle, without the need to carry out any aggregation. When applying the UFS+ model in the cogeneration cycle under study, the fuel and products of each production unit are defined, according to Tab. 4, while the productive structure can be seen in Figure 7. Obtaining unit exergetic costs occurs as discussed in item 2.2.

Table 4. Inputs and products of each production unit according to the UFS+ Model

| UFS Model | | | UFS+ Model | | |
|----------------|--|--|----------------|---|---|
| Component | Input | Product | Component | Input | Product |
| C ₁ | B ₁₀ + S _{2;1} | U _{2;1} + F _{2;1} | C ₁ | B ₁₀ + F _{V1;2} + S _{2;1} | U _{2;1} + F _{P2;1} |
| CC | B ₃ + S _{4;2} + X _{5;1} | U _{4;2} + F _{4;2} + X _{4;2} | CC | B ₃ + S _{4;2} + X _{5;1} | U _{4;2} + F _{P4;2} + F _{V4;2} + X _{4;2} |
| T _g | U _{4;5} + F _{4;5} + S _{5;4} | B _{11,10,12} | T _g | U _{4;5} + F _{P4;5} + S _{5;4} | B _{11,10,12} + F _{V5;4} |
| C ₂ | B ₁₁ + S _{7;6} | U _{7;6} + F _{7;6} | C ₂ | B ₁₁ + F _{V6;7} + S _{7;6} | U _{7;6} + F _{P7;6} |
| CND | U _{7;8} + F _{7;8} | S _{7;8} | CND | U _{7;8} + F _{P7;8} + F _{V7;8} | S _{7;8} |
| VLV | U _{8;9} + S _{9;8} | F _{9;8} | VLV | U _{8;9} + S _{9;8} | F _{P9;8} + F _{V9;8} |
| EVP | S _{6;9} | B ₁₄ + U _{6;9} + F _{6;9} | EVP | S _{6;9} | B ₁₄ + U _{6;9} + F _{P6;9} + F _{V6;9} |
| AMB | U _{5;1} + F _{5;1} + X _{4;2} | S _{5;1} + X _{5;1} | AMB | U _{5;1} + F _{P5;1} + F _{V5;1} + X _{4;2} | S _{5;1} + X _{5;1} |

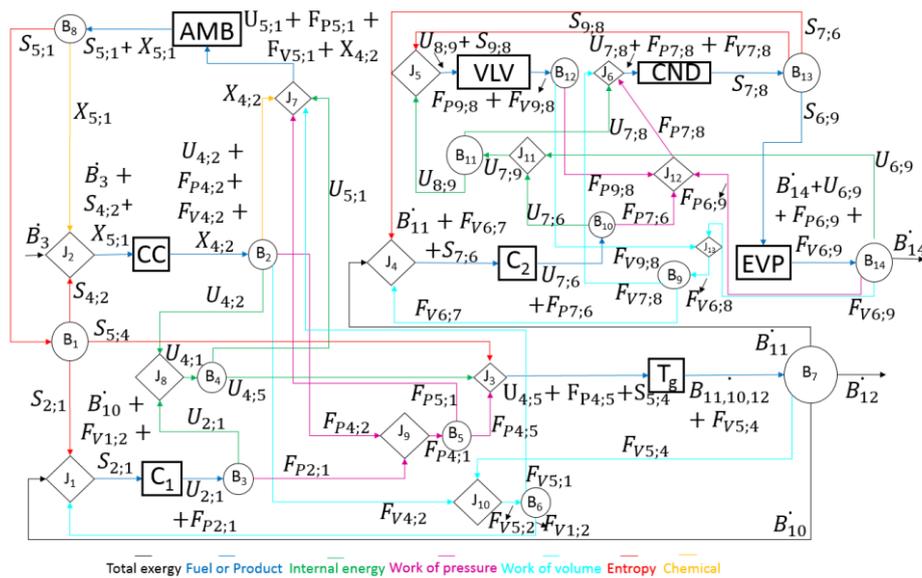


Figure 7. Productive diagram according to UFS+ Model

3. RESULTS

With the thermo-economic modeling presented in the methodology, it was possible to calculate the unit exergetic costs of the cogeneration cycle with a Brayton turbine and vapor compression refrigeration system. Table 5 and Table 6 present the k^* values of the fuel and product flows of all production units, as well as the k^* referring to the net power of the cycle and the heat taken from the environment to be cooled.

As explained in the methodology, the SPECO and E models do not allow complete isolation in cycles that present dissipative equipment, such as VLV and CND, since it is not possible to define the product of these components. The authors chose to add this equipment to C₂, forming the productive unit C₂-CND-VLV, however, according to the bases of thermo-economic modeling, the dissipative equipment could be added to any of the components of the structure.

Table 5. Unit exergetic costs (k^*) according to SPECO, E and E&S Models

| Description | SPECO | | | E Model | | | E&S Model | | |
|------------------------|------------------------------------|---------------------------|---------------------------|----------------|------------|---------------|-------------------|------------|---------------|
| | Flow | Value (kW) | k^* (kW/kW) | Flow | Value (kW) | k^* (kW/kW) | Flow | Value (kW) | k^* (kW/kW) |
| Fuel C_1 | B_{10} and B_1 | 1900 and 0 | 2.75 and 0 | B_{10} | 1900 | 2.75 | $B_{10}+S_{2;1}$ | 2068 | 2.68 |
| Product C_1 | B_2 | 1754 | 2.98 | $B_{2;1}$ | 1754 | 2.98 | $B_{2;1}$ | 1754 | 3.16 |
| Fuel CC | B_3 and B_2 | 8643 and 1754 | 1 and 2.98 | B_3 | 8643 | 1 | $B_3+S_{4;2}$ | 12949 | 1.32 |
| Product CC | B_4 | 8476 | 2.74 | $B_{4;2,5}$ | 3314 | 2.61 | $B_{4;2}$ | 6722 | 2.54 |
| Fuel Tg | B_4 | 8476 | 2.74 | $B_{4;5}$ | 5068 | 2.74 | $B_{4;5}+S_{5;4}$ | 5240 | 2.65 |
| Product Tg | B_{11}, B_{10}, B_{12} and B_5 | 9.09, 1900, 3139 and 3408 | 2.75, 2.75, 2.75 and 2.74 | $B_{11,10,12}$ | 5048 | 2.75 | $B_{11,10,12}$ | 5048 | 2.75 |
| Fuel C_2 -CND-VLV | B_{11} and B_6 | 9.09 and 4.20 | 2.75 and 5.34 | B_{11} | 9.09 | 2.75 | - | - | - |
| Product C_2 -CND-VLV | B_9 | 8,873 | 5.34 | $B_{9;6}$ | 4.66 | 5.34 | - | - | - |
| Fuel C_2 | - | - | - | - | - | - | $B_{11}+S_{7;6}$ | 10.79 | 2.35 |
| Product C_2 | - | - | - | - | - | - | $B_{7;6}$ | 7.387 | 3.43 |
| Fuel CND-VLV | - | - | - | - | - | - | $B_{7;9}$ | 2.712 | 3.43 |
| Product CND-VLV | - | - | - | - | - | - | $S_{7;9}$ | 41.54 | 0.22 |
| Fuel EVP | B_9 and B_{14} | 8.87 and 4.68 | 5.34 and 5.34 | $B_{9;6}$ | 4.66 | 5.34 | $B_{9;6}+S_{6;9}$ | 44.52 | 0.56 |
| Product EVP | B_6 | 4.20 | 5.34 | B_{14} | 4.68 | 5.34 | B_{14} | 4.677 | 5.34 |
| Fuel AMB | - | - | - | - | - | - | $B_{5;1}$ | 3408 | 2.67 |
| Product AMB | - | - | - | - | - | - | $S_{5;1}$ | 4646 | 1.96 |
| Net power | B_{12} | 3139 | 2.75 | B_{12} | 3139 | 2.75 | B_{12} | 3139 | 2.75 |
| Evaporator Heat | B_{14} | 4.68 | 5.34 | B_{14} | 4.68 | 5.34 | B_{14} | 4.68 | 5.34 |

As it can be deduced from Tab. 5, even though the two approaches are different, SPECO based on the physical structure and model E on the productive diagram, the results obtained for the products of the cogeneration system for these two methodologies were similar; in addition, there is not much complexity in the development of these models, with 11 and 10 equations being developed, respectively, in the mathematical model of cost allocation. According to Tab. 5, the value of k^* for the system products the net energy generated in the turbine and the heat removed from the environment by the evaporator were equal to 2.75 kW/kW and 5.34 kW/kW, respectively.

With the introduction of the concept of negentropy in the E&S model, it was possible to define the product of the condenser and, thus, isolate it in the productive diagram. It should be noted that this model is one of the best accepted today, as it was the first to formulate a method that allowed the isolation of equipment such as the CND. However, this methodology presents a critical point, the double consideration of the entropy term, since it is already considered as one of the parts of physical exergy, Eq. 1. The consequence of this double consideration is the contradiction to the second law of thermodynamics, since in this model some components have inconsistencies in the unit exergetic consumption, which are smaller than unity, which in practical terms means the generation of products in greater quantity than the inputs made available for this equipment. Such malfunction can be verified in the results referring to the E&S model in Tab. 5, whose flows originating in the condenser show $k^* < 1$. The costs of cogeneration products were maintained in relation to the SPECO and E models.

The H&S model solves the problem of double entropy consideration, in this way, the second law of thermodynamics is obeyed, and no equipment has unit exergetic costs less than unity, as shown in Tab. 6. Dissipative equipment of the VLV type is still being added to another component because there is no enthalpy variation, while this equipment consumes entropy, and it is not possible to define a product for this component. The complexity of developing the mathematical model of cost allocation is greater than that of the other models studied, requiring the development of 31 equations, while the E&S model required 24. The costs of cogeneration products were maintained in relation to the models already presented.

The UFS model was the first model that allowed the total disaggregation of the equipment of the system under analysis, however, this model presents the limitation of defining a product and a fuel for the case of isenthalpic devices, such as VLV, if the modeling of the fluid as an ideal gas is adopted. This limitation was not observed in this study and VLV was disaggregated from CND. As can be seen in Fig. 6, the UFS model presents a more complex productive diagram than the other models mentioned, presenting a greater number of flows and, consequently, a greater demand for

equations in the mathematical model of cost allocation, with a total of 47 equations. The results shown in Tab. 6, display that the costs of cogeneration products were maintained in relation to the models SPECO, E and H&S, presenting values of 2.75 kW/kW and 5.34 kW/kW, for the net power and heat of the evaporator.

The UFS+ model is an extension of the UFS model, developed to overcome the limitation highlighted above, regarding models that consider the working fluid as ideal air. Thus, if this consideration were made in this work, only this model would provide a complete disaggregation of the equipment that makes up the productive diagram. The UFS+ model was the most complex, being solved by a system composed of 58 equations. In addition, it is worth mentioning that the cogeneration cycle proposed in this work is theoretical and simple, not presenting great complexities and with a limited amount of equipment. The costs of the products of the cogeneration cycle were like the results presented for the SPECO, E, E&S, H&S and UFS models.

Table 6. Unit exergetic costs (k*) according to H&S, UFS and UFS+ Models

| Description | H&S Model | | | UFS Model | | | UFS+ Model | | |
|------------------------|---|------------|------------|---|------------|------------|---|------------|------------|
| | Flow | Value (kW) | k* (kW/kW) | Flow | Value (kW) | k* (kW/kW) | Flow | Value (kW) | k* (kW/kW) |
| Fuel C ₁ | B ₁₀ + S _{2;1} | 2068 | 2.97 | B ₁₀ + S _{2;1} | 2068 | 2.97 | B ₁₀ +F _{V1;2} + S _{2;1} | 2416 | 2.94 |
| Product C ₁ | H _{2;1} | 1900 | 3.23 | U _{2;1} + F _{2;1} | 1900 | 3.23 | U _{2;1} + F _{P2;1} | 2249 | 3.16 |
| Fuel CC | B ₃ + S _{4;2} +X _{5;1} | 11006 | 1.96 | B ₃ + S _{4;2} +X _{5;1} | 11006 | 1.96 | B ₃ + S _{4;2} +X _{5;1} | 11006 | 1.98 |
| Product CC | H _{4;2} +X _{4;2} | 8948 | 2.45 | U _{4;2} + F _{4;2} +X _{4;2} | 8948 | 2.42 | U _{4;2} + F _{P4;2} + F _{V4;2} +X _{4;2} | 8948 | 2.44 |
| Fuel Tg | H _{4;5} + S _{5;4} | 5220 | 2.66 | U _{4;5} +F _{4;5} + S _{5;4} | 5220 | 2.66 | U _{4;5} +F _{P4;5} + S _{5;4} | 6866 | 2.68 |
| Product Tg | B _{11,10,12} | 5048 | 2.75 | B _{11,10,12} | 5048 | 2.75 | B _{11,10,12} +F _{V5;4} | 6695 | 2.75 |
| Fuel C ₂ | B ₁₁ + S _{7;6} | 10.79 | 3.16 | B ₁₁ + S _{7;6} | 10.79 | 3.16 | B ₁₁ +F _{V6;7} + S _{7;6} | 12.56 | 3.66 |
| Product C ₂ | H _{7;6} | 9.09 | 3.75 | U _{7;6} + F _{7;6} | 9.09 | 3.75 | U _{7;6} + F _{P7;6} | 10.86 | 4.24 |
| Fuel CND-VLV | H _{7;9} | 44.26 | 5.01 | - | - | - | - | - | - |
| Product CND-VLV | S _{7;9} | 41.54 | 5.34 | - | - | - | - | - | - |
| Fuel CND | - | - | - | U _{7;8} + F _{7;8} | 44.26 | 5.15 | U _{7;8} +F _{P7;8} +F _{V7;8} | 44.26 | 5.15 |
| Product CND | - | - | - | S _{7;8} | 42.70 | 5.34 | S _{7;8} | 42.70 | 5.34 |
| Fuel VLV | - | - | - | U _{8;9} + S _{9;8} | 2.25 | 5.17 | U _{8;9} + S _{9;8} | 2.25 | 5.22 |
| Product VLV | - | - | - | F _{9;8} | 1.09 | 10.63 | F _{P9;8} +F _{V9;8} | 1.09 | 10.73 |
| Fuel EVP | S _{6;9} | 39.84 | 5.34 | S _{6;9} | 39.84 | 5.34 | S _{6;9} | 39.84 | 5.34 |
| Product EVP | B ₁₄ +H _{6;9} | 39.84 | 5.34 | B ₁₄ +U _{6;9} + F _{6;9} | 39.84 | 5.34 | B ₁₄ +U _{6;9} + F _{P6;9} +F _{V6;9} | 39.84 | 5.34 |
| Fuel AMB | H _{5;1} +X _{4;2} | 5800 | 2.56 | U _{5;1} + F _{5;1} +X _{4;2} | 5800 | 2.56 | U _{5;1} +F _{P5;1} + F _{V5;1} +X _{4;2} | 5800 | 2.60 |
| Product AMB | S _{5;1} +X _{5;1} | 2703 | 5.49 | S _{5;1} +X _{5;1} | 2703 | 5.49 | S _{5;1} +X _{5;1} | 2703 | 5.58 |
| Net power | B ₁₂ | 3139 | 2.75 | B ₁₂ | 3139 | 2.75 | B ₁₂ | 3139 | 2.75 |
| Evaporator Heat | B ₁₄ | 4.68 | 5.34 | B ₁₄ | 4.68 | 5.34 | B ₁₄ | 4.68 | 5.34 |

4. CONCLUSION

In this study, a thermoeconomic analysis of a cogeneration system that uses a Brayton cycle turbine and a R134a gas vapor compression refrigeration system was carried out to produce 3 MW of electricity and 10 TR, using natural gas as fuel. The results obtained indicated that the unit exergetic costs of the products of the cogeneration cycle, electrical power and evaporator heat were 2.75 kW/kW and 5.34 kW/kW, in the analyzes carried out from the all the models under study (SPECO, E, E&S, H&S and UFS+). It appears from the analyzes carried out that the higher the level of exergy disaggregation proposed by a model, the greater the level of complexity presented by it, both in the development of the production diagram and in the number of equations needed to solve the mathematical model of allocation of costs. Thus, when choosing a thermoeconomic methodology, it is necessary to define the focus of the study very well so that the required analyzes are obtained through a technique in which the complexity fits the limits of the research.

5. ACKNOWLEDGEMENTS

The authors are thankful to the PUC Minas, FAPEMIG, CNPq and CAPES.

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