



24th COBEM - 2017



24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-1938

ON THE PHYSICAL EXERGY DISAGGREGATION LEVELS FOR THE ISOLATION OF DISSIPATIVE COMPONENTS IN THE THERMOECONOMIC PRODUCTIVE DIAGRAMS

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Abstract. *Thermoeconomics connects Thermodynamics and Economics. In order to carry out a thermoeconomic analysis, a productive structure of the plant must be defined, generally represented by means of a productive diagram, showing graphically the products and fuels of each subsystem and the interconnection between them and with the environment. Exergy is the main thermodynamic magnitude used. Depending on the analysis, different levels of disaggregation of the subsystems and of the exergy flows are required. Sometimes, exergy flows are disaggregated into its thermal and mechanical components. However, most energy system has dissipative components (condensers, intercoolers and valves), whose products and/or fuels cannot be defined in terms of total exergy nor in terms of its thermal and mechanical components. In order to overcome this limitation, in the last years, new kinds of physical exergy disaggregation have been introduced in thermoeconomics as alternatives for the treatment of the dissipative components. Various levels of physical exergy disaggregation were proposed. This work shows that, for each kind of dissipative component, there is an adequate exergy disaggregation level that allows defining its fuels and products.*

Keywords: *Thermoeconomics, Exergy Components, Dissipative Units, Productive Diagrams.*

1. INTRODUCTION

Thermoeconomics can be considered a new science which, by connecting Thermodynamics and Economics, provides tools to solve problems in complex energy systems that can hardly or not be solved using conventional energy and economic analysis techniques, as for instance a rational price assessment to the products of a plant based on physical criteria, local optimization and operation diagnosis (Erlach et al., 1999).

Most analysts agree that exergy is the most adequate thermodynamic magnitude to associate with cost, since it contains information from the second law of thermodynamics and accounts for energy quality, i.e., an exergy analysis locates and quantifies the irreversibilities of the processes and systems (Valero et al., 2006).

Sometimes, under a thermoeconomic analysis, it is necessary to consider the components as a group of subsystems and/or the exergy flows consisting of several components, because the more disaggregated is the system the more accurate are the results (Torres et al., 1996). For an accurate local optimization and operation diagnosis, for instance, total disaggregation of the components of the thermal systems is an important and mandatory required step. In other words, each thermoeconomic analysis requires a specific aggregation level of the components and flows.

In order to carry out a thermoeconomic analysis, a productive structure of the system is defined, which can be represented by means of a productive diagram, showing graphically the productive purpose (products and fuels) of each subsystem and the productive interaction between them and the environment (Torres et al., 1996).

According to Lazzaretto and Tsatsaronis (2006), by considering physical exergy disaggregated into thermal and mechanical components, the accuracy of results in thermoeconomics is improved and the complexity of the model is increase. However, most energy system has dissipative components (condensers, intercoolers and valves), whose product cannot be defined in terms of total exergy nor in terms of thermal and mechanical exergy components.

Taking this in mind, in the last ten years, new kinds of physical exergy disaggregation have been introduced in thermoeconomic analysis as consistent alternative way to disaggregate and isolate the dissipative components of the thermal systems (Santos, Nascimento and Lora, 2006; Santos *et al.*, 2009; Lourenço, Santos and Donatelli, 2011; Santos, Lourenço and Silva, 2012; Lourenço, 2016), which was a thermoeconomic challenge until 2006. Thus, this work aims at showing that, for each kind of dissipative components (condensers, intercoolers and water/steam valves, air/gas valves, etc.), there is an adequate exergy disaggregation level that allows defining their fuels and products.

2. PHYSICAL EXERGY DISAGGREGATION LEVELS

In order to carry out the thermoeconomic modeling, the total physical exergy and its components need to be calculated. Figures 1 and 2 summarize the procedures to calculate the physical exergy and its components for physical flows representing air or gases (modelled as ideal gases) and water or steam (real fluids), respectively.

$$E^{Ph} = \underbrace{\dot{m} \cdot \int_{T_0}^T c_v \cdot dT}_U + \underbrace{\dot{m} \cdot \int_{v_0}^v p \cdot dv}_{FV} + \underbrace{\dot{m} \cdot \int_{p_0}^p v \cdot dp}_{FP} - \underbrace{\dot{m} \cdot T_0 \cdot \int_{T_0}^T \frac{c_p}{T} \cdot dT + \dot{m} \cdot R \cdot T_0 \cdot \ln\left(\frac{P}{P_0}\right)}_S$$

UFS+ Model

$$\underbrace{\dot{m} \cdot \int_{T_0}^T c_v \cdot dT}_U + \underbrace{\dot{m} \cdot \int_{v_0}^v p \cdot dv + \dot{m} \cdot \int_{p_0}^p v \cdot dp}_F - \underbrace{\dot{m} \cdot T_0 \cdot \int_{T_0}^T \frac{c_p}{T} \cdot dT + \dot{m} \cdot R \cdot T_0 \cdot \ln\left(\frac{P}{P_0}\right)}_S$$

UFS Model

$$\underbrace{\dot{m} \cdot \int_{T_0}^T c_v \cdot dT + \dot{m} \cdot \int_{v_0}^v p \cdot dv + \dot{m} \cdot \int_{p_0}^p v \cdot dp}_H - \underbrace{\dot{m} \cdot T_0 \cdot \int_{T_0}^T \frac{c_p}{T} \cdot dT + \dot{m} \cdot R \cdot T_0 \cdot \ln\left(\frac{P}{P_0}\right)}_S$$

H&S Model

$$\underbrace{\dot{m} \cdot \int_{T_0}^T c_v \cdot dT + \dot{m} \cdot \int_{v_0}^v p \cdot dv + \dot{m} \cdot \int_{p_0}^p v \cdot dp - \dot{m} \cdot T_0 \cdot \int_{T_0}^T \frac{c_p}{T} \cdot dT}_{E^T} + \underbrace{\dot{m} \cdot R \cdot T_0 \cdot \ln\left(\frac{P}{P_0}\right)}_{E^M}$$

E^{TEM} Model

$$\underbrace{\dot{m} \cdot \int_{T_0}^T c_v \cdot dT + \dot{m} \cdot \int_{v_0}^v p \cdot dv + \dot{m} \cdot \int_{p_0}^p v \cdot dp - \dot{m} \cdot T_0 \cdot \int_{T_0}^T \frac{c_p}{T} \cdot dT + \dot{m} \cdot R \cdot T_0 \cdot \ln\left(\frac{P}{P_0}\right)}_E$$

E Model

Figure 1. Exergy Disaggregation Level and Thermoeconomic Models for Ideal Gases

$$E^{Ph} = \underbrace{\dot{m} \cdot (u - u_0)}_U + \underbrace{\dot{m} \cdot p_0 \cdot (v - v_0)}_{FV} + \underbrace{\dot{m} \cdot v \cdot (p - p_0)}_{FP} - \underbrace{\dot{m} \cdot T_0 \cdot (s - s_0)}_S$$

UFS+ Model

$$\underbrace{\dot{m} \cdot (u - u_0)}_U + \underbrace{\dot{m} \cdot p_0 \cdot (v - v_0) + \dot{m} \cdot v \cdot (p - p_0)}_F - \underbrace{\dot{m} \cdot T_0 \cdot (s - s_0)}_S$$

UFS Model

$$\underbrace{\dot{m} \cdot (u - u_0) + \dot{m} \cdot p_0 \cdot (v - v_0) + \dot{m} \cdot v \cdot (p - p_0)}_H - \underbrace{\dot{m} \cdot T_0 \cdot (s - s_0)}_S$$

H&S Model

$$\underbrace{\dot{m} \cdot (u - u_0) + \dot{m} \cdot p_0 \cdot (v - v_0) + \dot{m} \cdot v \cdot (p - p_0) - \dot{m} \cdot T_0 \cdot (s - s_0)}_?$$

E^{TEM} Model

$$\underbrace{\dot{m} \cdot (u - u_0) + \dot{m} \cdot p_0 \cdot (v - v_0) + \dot{m} \cdot v \cdot (p - p_0) - \dot{m} \cdot T_0 \cdot (s - s_0)}_E$$

E Model

Figure 2. Exergy Disaggregation Levels and Thermoeconomic Models for Real Fluids

Figures 1 and 2 also show the thermoeconomic models (E, E^{TEM}, H&S, UFS and UFS+) corresponding to each disaggregation level (I, IIa, IIb, III and IV). For E^{TEM} Model, the components are not explicit in the physical exergy equation for real fluid (Fig. 2). Thermal and mechanical components of physical exergy for real fluids can be calculated. However, this procedure contains arbitrariness. Figure 2 shows that, for ideal gas, this arbitrariness does not occur.

	Model				
	UFS+	UFS	H&S	E ^T E ^M	E

Figure 4. Definition of Fuels and Products for each Dissipative Component and Thermoeconomic Model

To define the products and fuels of any productive or dissipative component it is necessary to analyze the flows of exergy (total or into its components), described in Fig. 3, crossing each subsystem of the plant to determine if it is input (fuel) or output (product). For this definition, it takes into account if the contribution of the exergy component under consideration is positive or negative in the total exergy equation (Fig. 1 and 2) and if it is increasing or decreasing between the initial and final state of the subsystem. If the contribution of the exergy component is positive in the total exergy equation (E, E^T, E^M, H, U, F, FP and FV), increasing flows of this magnitude are output and decreasing flows are input. If the contribution is negative (S), increasing flows are input and decreasing flows are output.

For instance, for E Model in which the products and fuels are defined based on total physical exergy (E), the fuels and product of the subsystems are productive flows (E_{j:k}) representing the total physical exergy variations between two physical flows (E_j and E_k). Once that total physical exergy (E) is a positive contribution, if this magnitude increases between the initial and final state of the subsystem, the productive flows (E_{j:k}) is a positive value representing the product and, if it decreases between the initial and final state of the subsystem, the productive flows (E_{j:k}) is the fuel. For E^TE^M Model, there are productive flows representing the thermal and/or mechanical components (E^T_{j:k} and/or E^M_{j:k}) due to these magnitudes variations between two physical flows (E^T_j and E^T_k and/or E^M_j and E^M_k).

For H&S Model, the fuel and products are defined using productive flows based on enthalpic (H_{j:k}) and the entropic (S_{j:k}) terms of the physical exergy. However, the entropic term (S_{j:k}) has negative contribution to the total exergy. Consequently, the entropic term (S_{j:k}) is product when the working fluid entropy decreases and it is fuel when the working fluid entropy increases. The entropic term (S_{j:k}) has the same meaning for UFS and UFS+ Model, in which the remaining terms are all enthalpic components and all of them have positive contribution to the total physical exergy. In other words, besides the entropic term (S_{j:k}), the UFS Model has internal energy (U_{j:k}) and flow work (F_{j:k}) terms, while UFS+ Model has internal energy (U_{j:k}), volume flow work (FV_{j:k}) and pressure flow work (FP_{j:k}) terms.

Figure 4 shows that E and E^TE^M Models cannot define the product of any dissipative component and H&S Model cannot define the product of the valves. UFS Model cannot define the product of the valve expanding ideal gas (GV). UFS+ Model is able to deal with all the dissipative components, once that it allows defining its fuels and product.

5. THERMOECONOMIC PRODUCTIVE DIAGRAMS

The productive diagrams of the cogeneration plant according to each thermoeconomic model (E, H&S, UFS and UFS+) are presented in Figs. 5, 6, 7 and 8 (respectively). The productive diagram for the E^TE^M Models is not presented because this thermoeconomic model do not present any advantages of the dissipative components isolation compared to the E Model. However, the E^TE^M Models increases the complexity of the productive diagram compared to the E Model.

A thermoeconomic productive diagram define the productive propose of the subsystems (products and fuels), as well as the distribution of the external resources and internal product throughout the system. This kind of diagram shows clearly and graphically how the products of a given subsystem is distributed to be used as input in another subsystem or as a final product of the plant. The rectangles are the real units (or subsystems) that represent the actual equipment of the system. The rhombus and the circles are fictitious units called junction and bifurcations, respectively. Each productive units has inlet and outlet arrows, that represent its fuel (or resource) and products, respectively.

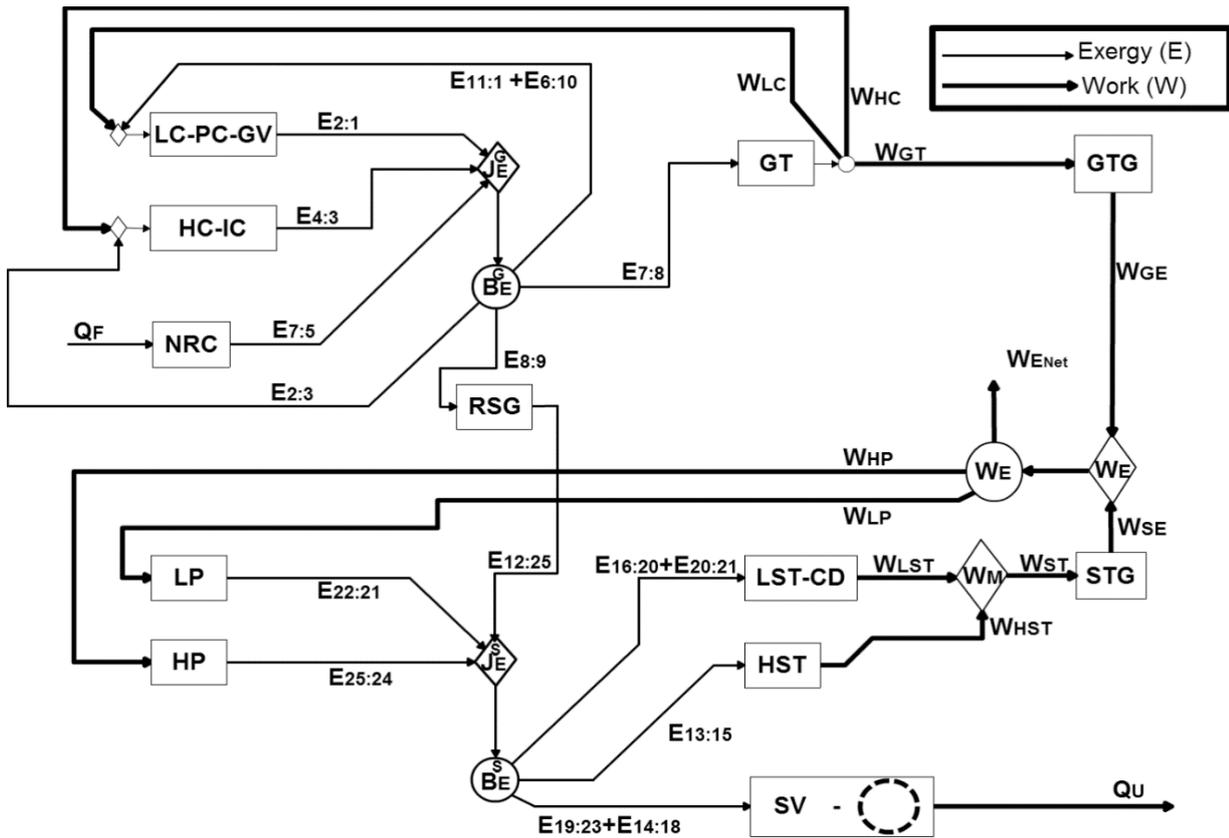


Figure 5. Productive Diagram of the Cogeneration Plant according to E Model (Level I)

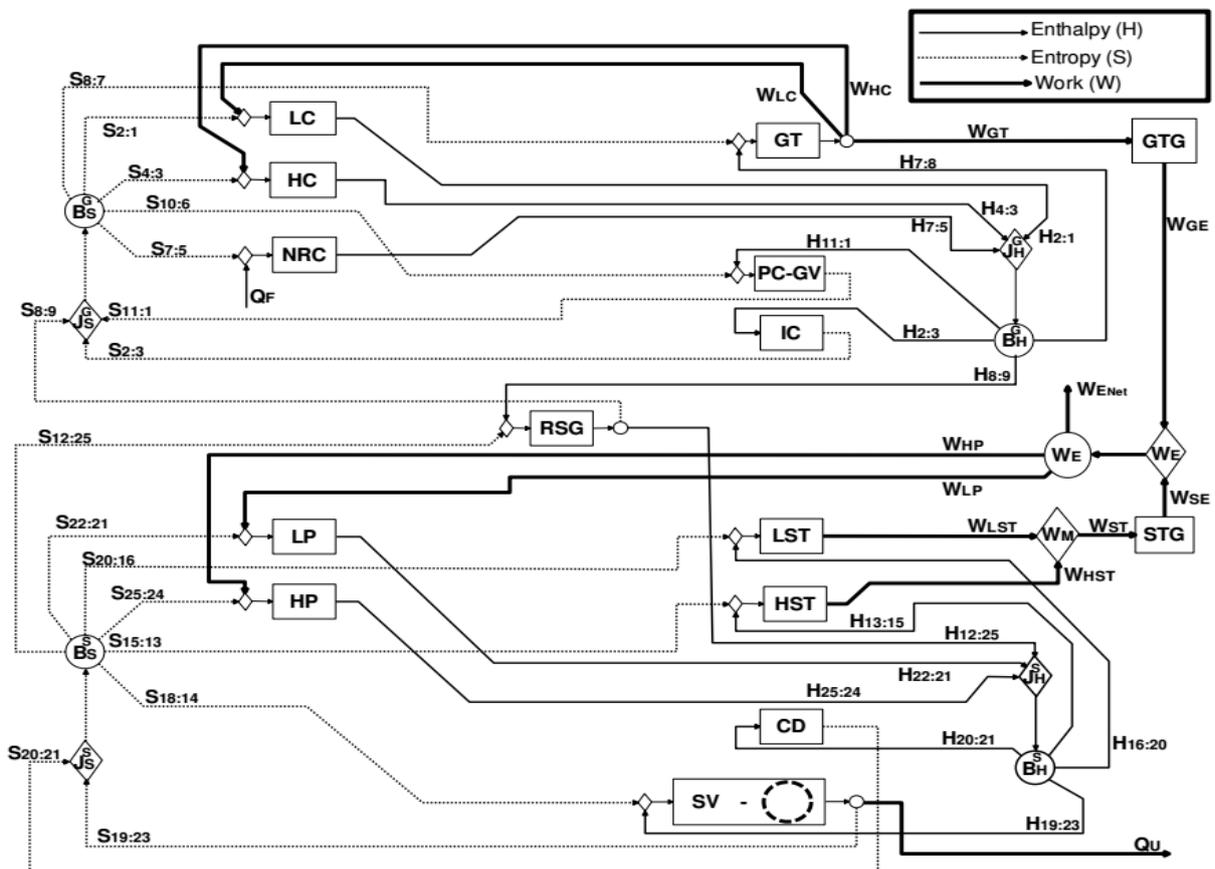


Figure 6. Productive Diagram of the Cogeneration Plant according to H&S Model (Level IIb).

5.1 E Model: level I

Figure 5 shows that E Model cannot isolate the dissipative components and these components must be analyzed joined up to the productive components. However, the decision is more or less arbitrary. In this case, the condenser is joined up to the low pressure steam turbine (LST-CD), intermediate cooler together with the high pressure compressor (HC-IC), the precooler and the gas valve is joined up to the low pressure compressor (LC-PC-GV) and the steam valve is analyzed together with the industrial process (SV- O) fuel by the useful heat produced in the cogeneration plant.

5.2 H&S Model: level IIb

Figure 6 shows that H&S Model can isolate some dissipative components: condenser (CD), intermediate cooler (IC) and precooler (PC). These components decrease the enthalpy and the entropy of the working fluid. Once that the enthalpy has a positive contribution to the total exergy, this magnitude is the fuel of these dissipative components. On the other hand, entropy has a negative contribution to the exergy and, consequently, entropy is their product.

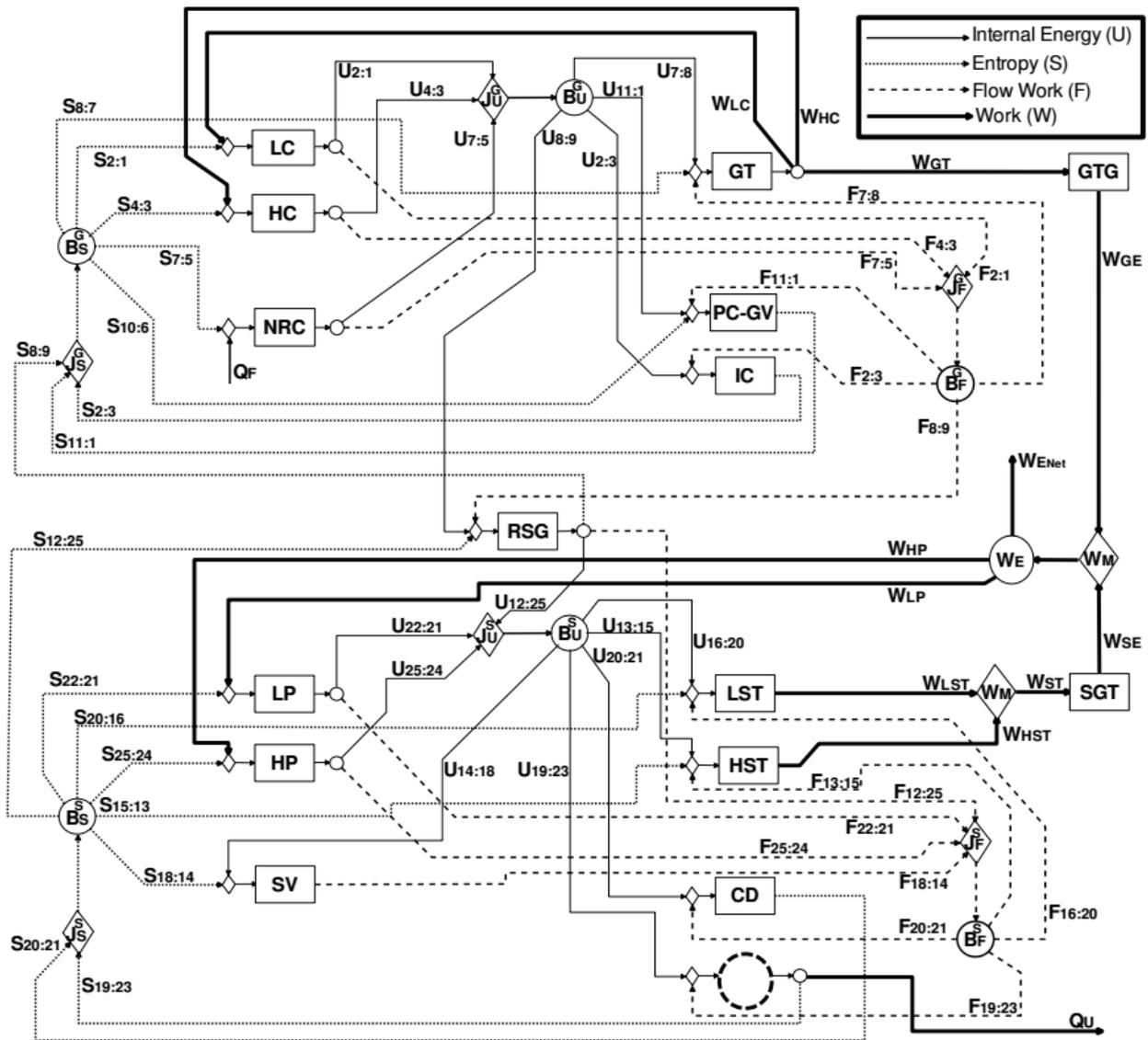


Figure 7. Productive Diagram of the Cogeneration Plant according to UFS Model (Level III)

Figure 6 show that in a productive diagram defined according to H&S Model the valves stay analyzed together with others subsystems: the gas valve is joined up to the precooler (PC-GV) and the steam valve is analyzed together with the industrial process (SV-O). The valves are a different kind of dissipative component, generally modelled as isenthalpic process, in which working fluid enthalpy do not varies. Only the working fluid entropy varies in the valves.

5.3 UFS Model: level III

Figure 7 shows that UFS Model can isolate the steam valve (SV). However, the gas valve (GV) stay analyzed joined up to the precool (PC-GV). Although the enthalpy does not varies in the steam valve (SV), the UFS Model allows isolating this dissipative component because it is an extension of the H&S Model by disaggregating the enthalpy (H) into internal energy (U) and flow work (F) terms. Both working fluid internal energy and working fluid flow work has positive contribution to the total physical exergy and they varies in the steam valve. The working fluid internal energy decreases and the working fluid flow work increases the same quantity in order to maintain constant the working fluid enthalpy from de inlet to the outlet. Consequently, the first is the fuel and the last is the product of the steam valve (SV).

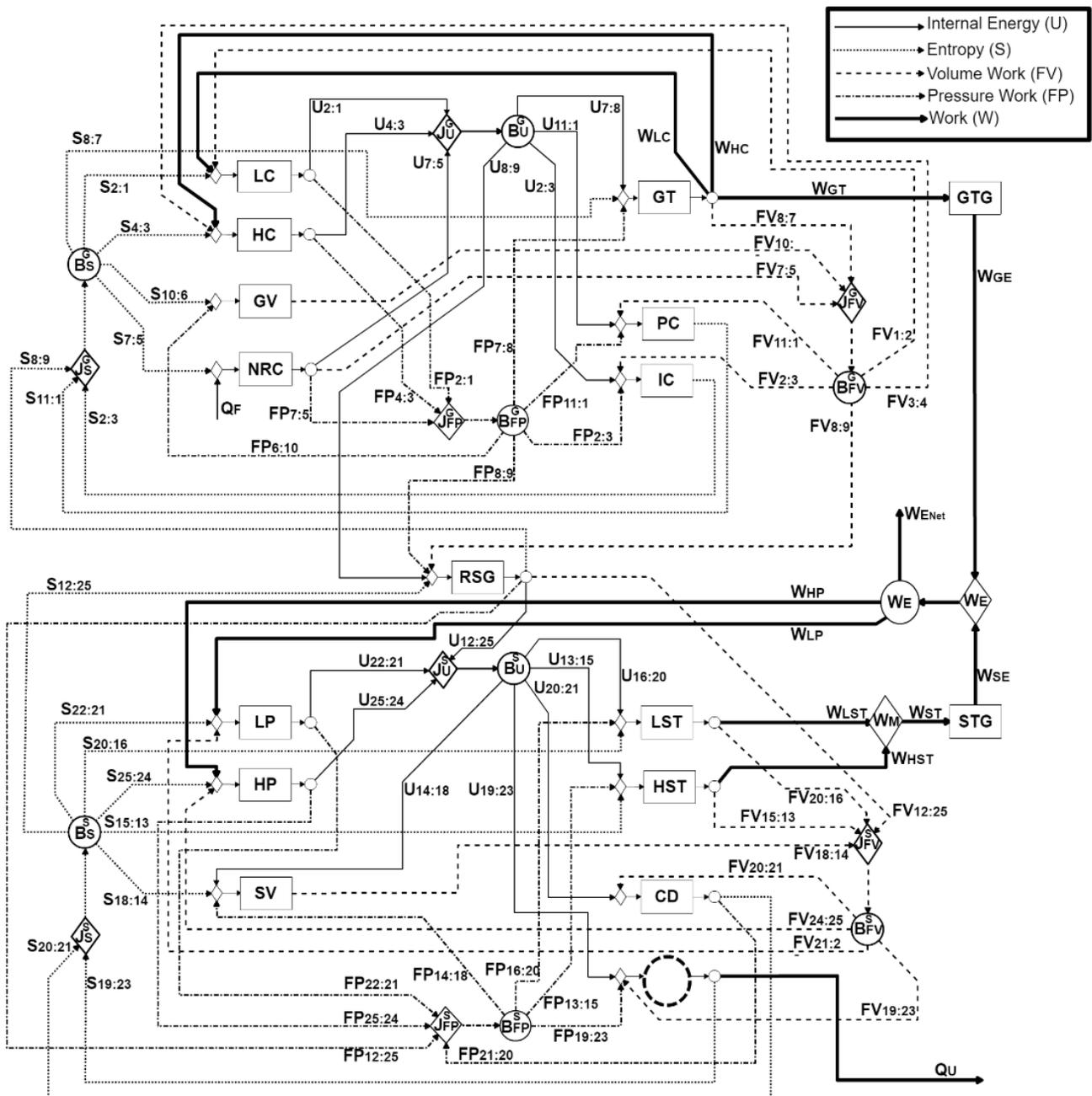


Figure 8. Productive Diagram of the Cogeneration Plant according to UFS+ Model (Level IV)

For ideal gases, the enthalpy and its components (internal energy and flow work) depend on the temperature only. In other words, an isenthalpic process for ideal gases is an isothermal process. This means that internal energy and flow work do not varies in the gas valve (GV). Once that, only the working fluid entropy varies in the gas valve, UFS Model allows defining its fuel only, because the product cannot be defined in terms of internal energy nor flow work. Thus, UFS Model can isolate the steam valve (SV), but the gas valve (GV) stay analyzed joined up to the precool (PC-GV). From the thermoeconomic point of view, steam valve and gas valves are different kinds of dissipative components.

5.4 UFS+ Model: level IV

Figure 8 shows that UFS+ Model is able to isolate all dissipative components, it is an extension of the UFS Model by disaggregating the flow work (F) into volume flow work (FV) and pressure flow work (FP) terms. Both working fluid volume flow work and pressure flow work has positive contribution to the total physical exergy and they varies in the gas valve. The working fluid pressure flow work decreases and the working fluid volume flow work increases the same quantity in order to maintain constant the working fluid flow work from de inlet to the outlet. Consequently, the first is fuel and the last is product of gas valve (GV). Once that the working fluid entropy increases in the gas valve, this magnitude is also a fuel. Internal energy is not fuel nor product because this magnitude does not vary in the gas valve.

6. CONCLUSIONS AND CLOSURE

This work aimed at showing that, for each kind of dissipative components, there is an adequate exergy disaggregation level that allows defining their fuels and products. For this purpose, the procedures to calculate the physical exergy and its components for physical flows representing air or gases (ideal gases) and water or steam (real fluids) were presented. Five thermoeconomic models (E, E^{TEM}, H&S, UFS and UFS+) based on different physical exergy disaggregation level (I, IIa, IIb, III and IV) were used in a combined cycle cogeneration plant, with five different dissipative components: condenser, intermediate cooler, precooler, gas valve and steam valve.

The productive diagram based on each thermoeconomic models allows conclude that: (i) E Model cannot isolate the dissipative components and these components must be analyzed joined up to other productive components; (ii). E^{TEM} Model increase the complexity of the productive diagram, without isolate any dissipative component; (iii) if there is a condenser or a cooler in the studied system, it is necessary the H&S Model; (iv) if there is a valve expanding real fluid, it is necessary the UFS Model; (v) UFS+ Model is the only model able to isolate all the dissipative components.

Although exergy disaggregation is an alternative for total disaggregation of systems composed with dissipative components, the complexity increases due to the number of junctions, bifurcations and disaggregated flows. However, this is required during local optimization and diagnosis and to improve the accuracy of the results during cost allocation.

7. ACKNOWLEDGEMENTS

The authors are grateful to FAPES, CAPES, ANP and TEVISA for the financial support.

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