FUEL AND PRODUCT DEFINITIONS IN COST ACCOUNTING EVALUATIONS: IS IT A SOLVED PROBLEM?

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ABSTRACT

Exergoeconomic cost evaluations are based on the principle that costs are apportioned among mass and energy streams in proportion to the exergy that is carried by the Fuel and Product streams of the energy system components. The Specific Exergy Costing (SPECO) method was developed to find a general and unambiguous "process based" criterion to define the Fuel and Product of each component based on the record of all additions and removals of exergy to and from the mass and energy streams of the real energy system. This criterion in conjunction with the so called Fuel and Product Rules allows one to directly extract the exact number of auxiliary equations that are needed to evaluate costs.

Several examples have been already shown in the last years to demonstrate the reduction of ambiguities in the Fuel and Product definitions and in turn in cost calculations deriving by the use of the SPECO approach. Other more specific examples of application to components having a "double purpose" are considered in this paper to compare the SPECO approach with other approaches, and to demonstrate the more reliable costs obtained by the former also in these cases.

INTRODUCTION

Exergoeconomics is aimed at evaluating the exergy and monetary costs associated with all mass and energy streams in the energy system. The basic principle of all exergoeconomic methodologies proposed in the literature consists in apportioning the costs of the input streams according to the exergy carried by the Fuel and Product of the system components. Thus, in addition to the exergy values associated with mass and energy streams calculated by the exergy analysis, this criterion of cost allocation requires a correct formulation of Fuel and Product of each system component. On the other hand, there is an intrinsic degree of subjectivity in the Fuel and Product definitions, i.e. there is more than one definition that fulfills the component exergy balance. And additional ambiguities may derive from the definition of the component boundaries which may include more than a single device.

Some of the basic exergoeconomic papers written in the literature ([1], [2], [3], [4]) focused on the direct relationship between Fuel and Product and associated costs but did not put specific emphasis on the need of unambiguous Fuel and Product definitions, implicitly assuming that these definitions are "given" by the exergy analysis and accepting a certain degree of flexibility in their formulation depending on the role of the component in the overall system structure. Exergoeconomic functional approaches ([5], [6], [7]) gave instead a basic importance to the formulation of Fuel and Product of the system components, which were called component "functions" and specifically defined according to the role and location of the component in the system structure. These approaches require a preliminary analysis of the overall systems and its components to decide all the "productive" interactions between each component and the other system components. In [8] it was named "a logical approach" to underline that the functional interactions among system components depend on how each component "serves" the other system components.

The Specific Exergy Costing Method (SPECO) [9] started from a basically different idea for the formulation of the components Fuel and Product, consisting in taking a record of all exergy additions and removals that are performed by each component on the mass and energy streams of the system. Exergy additions and removals were considered as parts of the Product and the Fuel, respectively. Specific exergies give the name to the method because they are to be calculated when different mass streams join within the component. The SPECO idea simply derives from observing that the productive "function" of the component is independent of the presence of the other components in the system, depending on its behavior only. Thus, the component interacts with exergy additions to and removals from the rest of the system only through the mass and energy streams crossing its boundaries. Accordingly, the formulation of each component Fuel and Product involves only exergy streams associated with these mass and energy streams. This concept implies that the exergy links of the component with the rest of the system remain the same as those of the system flowsheet (often named "physical structure") because all the "productive" interactions between each component and the rest of the system are defined within the component boundaries. So, the "productive structure" does not alter the physical structure of the system, and it is built by analyzing each component separately without the need of a specific analysis of the total system configuration. In this first "SPECO" paper exergy and monetary costs were calculated using the Last In First Out (LIFO) criterion. In [10] the SPECO approach was extended to the calculation of average costs, and a computer code was developed to take an automatic record of all exergy and cost additions to and removals from mass and energy streams in order to avoid the need of defining in advance Fuel and Product of each component. This approach was further extended and developed and finally lead to a general criterion to formulate

Fuel and Product and the associated costs ([11], [12], [13)]. In particular in [13] it was shown how to apply the general addition/removal criterion in the formulation of Fuel and Product, and general F and P rules were formulated to obtain the necessary and sufficient number of cost equations in agreement to the Fuel and Product definitions. Several examples of applications were presented to underline the general applicability of the SPECO criterion, which basically consists in

i) calculating of the exergy differences between outlet and inlet of the component along each mass and energy stream crossing the component boundaries,

ii) checking the sign of these differences (positive and negative differences correspond to exergy additions and removals, respectively);

iii) including in the Product only the desired exergy additions, and leaving exergy removals and undesired exergy additions on the Fuel side.

Only in some cases in which chemical transformations are involved (e.g., in a gasification reactor in which a solid fuel is transformed into a gas) it may be meaningful to consider input exergies on the Fuel side and output exergies on the Product side.

This paper focuses on some specific components in which there might be uncertainties in the definition of Fuel and Product and in the consequent auxiliary cost equations, and tries to remove this uncertainties by comparing the results of the application of the SPECO method with a possible alternative approach under changes of the component behavior.

EXAMPLES OF APPLICATION

Heat exchangers in which both cooling and heating are desired and useful

The SPECO criterion involving exergy differences in the Fuel and Product definitions is compared to a different approach according to which the exergy at the outlet and inlet of the component are to be considered on the Product and Fuel side, respectively. The comparison is performed using two kinds of heat exchangers having separated or mixed streams, respectively. In both kinds of heat exchangers the cooling on the hot side and heating on the cold side are useful and desired to improve the exergy efficiency of the overall system in which the heat exchangers are included.

The *criterion to used here to "evaluate" the F and P definitions and associated costs consists in checking the variation of the exergy efficiency and the cost of product of the component under a change of its behavior*.

Separate streams

This first example refers to a heat exchanger in which the hot stream to be cooled and the cold stream to be heated are separate. Both cooling of the hot stream and heating of the cold stream are desired and useful to improve the exergy efficiency of the total system. A practical application is the intercooler in a multi-stage compressor (see Fig.1 [1]) in which the decrease of the exergy at hot side reduces the compression work whereas the increase of the exergy on the cold side is used to increase the temperature of the hot reservoirs, the heat of which is then supplied to a reheated expansion (not appearing in the figure). The heat exchanger flowsheet is shown in Fig.2.

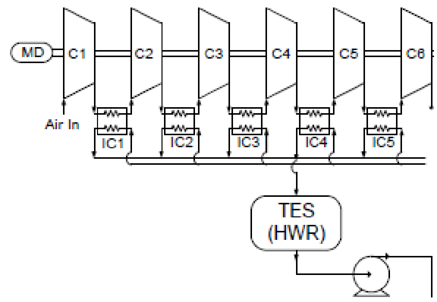

Figure 1: Multi-stage compression with heat recovery from intercooling (see, [14])

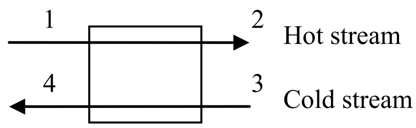

Fig.2. Heat exchanger with separate streams

According to the SPECO method the addition of exergy to the cold stream is desired and therefore it makes up the product, whereas the Fuel is equal to the exergy needed to generate the Product, i.e to the removal of exergy from the hot stream

$$\dot{E}_P = \dot{E}_4 - \dot{E}_3 \qquad \dot{E}_F = \dot{E}_1 - \dot{E}_2 \qquad \text{(SPECO)} \qquad (1)$$

Instead, considering the heat exchanger as having the "double purpose" (named in the following DP) of heating the output stream 4 and cooling the output stream 2 leads to the following definition of Product and to the consequent (accoding to exergy balance) definition of Fuel (see, e.g., [14])

$$\dot{E}_P = \dot{E}_2 + \dot{E}_4 \qquad \dot{E}_F = \dot{E}_1 + \dot{E}_3 \qquad \text{(DP)} \qquad (2)$$

Thus, using the SPECO approach (Equations (1)), the exergy efficiency of the heat exchanger is

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{m}_{cold}(e_4 - e_3)}{\dot{m}_{hot}(e_1 - e_2)} \qquad \text{(SPECO)} \qquad (3)$$

where e indicates a specific exergy (kJ/kg) and $\dot{m}$ a mass flow rate, whereas using the DP approach (Equations (2))

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{E}_2 + \dot{E}_4}{\dot{E}_1 + \dot{E}_3} \qquad \text{(DP)} \qquad (4)$$

The cost balance of the component indicates that the sum of all cost flow rates at the inlet is equal to the sum of all cost flow rates at the outlet

$$c_1\dot{E}_1 + c_3\dot{E}_3 = c_2\dot{E}_2 + c_4\dot{E}_4 + \dot{Z} \qquad (5)$$

where c represent specific costs (\$/kJ), $\dot{E}$ are exergy flow rates (kJ/s) and $\dot{Z}$ (\$/s) amortization cost flow rates. The latter are neglected here for simplicity. Specific costs c_1 and c_3 are assumed to be known and equal to 1 (kJ/kJ). The cost balance is not sufficient to calculate the two unknown costs c_2 and c_4 of the outlet streams. The *F* rule of the SPECO method states that the average specific cost at which the exergy is removed in the component is equal to the average specific cost at which the same exergy was supplied in the upstream components. This rule applied to the Fuel defined according to the SPECO criterion (Eq. 1) supplies the auxiliary equation

$$c_1 = c_2 \qquad \text{(SPECO)} \qquad (6)$$

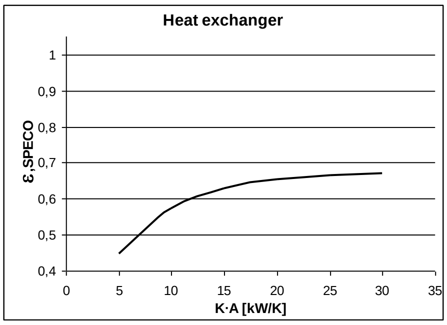

Figure 3: SPECO exergetic efficiency of the heat exchanger in Fig.2.

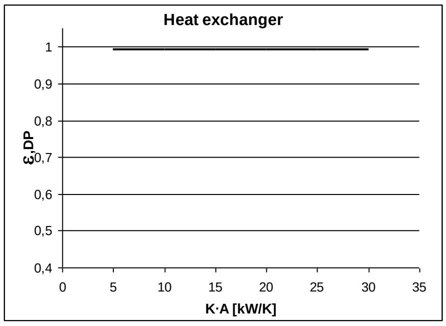

Figure 4: DP exergetic efficiency of the heat exchanger in Fig.2.

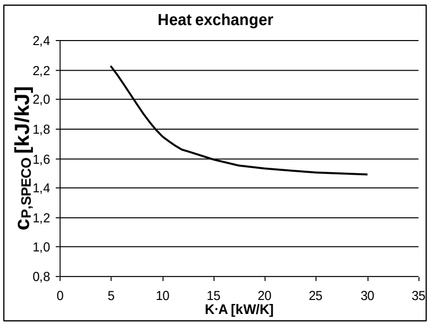

Figure 5: SPECO cost of product of the heat exchanger in Fig.2.

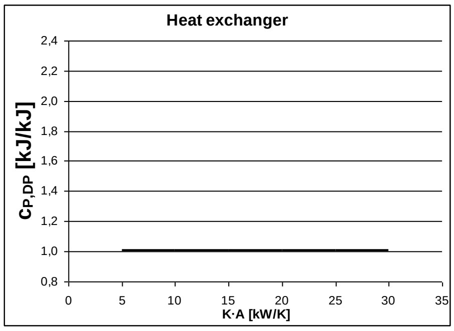

Figure 6: DP cost of product of the heat exchanger in Fig.2.

Instead, the DP exergy efficiency imposes the P rule to be used, which states that the component products ($\dot{E}_2$ and $\dot{E}_4$) are generated at the same unit costs, i.e.

$$c_2 = c_4 \qquad \text{(DP)} \qquad (7)$$

According to the Product definitions given in Eqs. (1) and (2) the costs per unit of exergy of the products (c_P) are

$$c_P = \frac{c_4\dot{E}_4 - c_3\dot{E}_3}{\dot{E}_4 - \dot{E}_3} \qquad \text{(SPECO)}$$

$$c_P = c_2 \qquad \text{(DP)} \qquad (8)$$

The heat exchanger behavior was simulated by considering air on the hot side and water on the cold side. Mass flow rates, temperatures and pressures at the inlet were assumed to be fixed input data ($\dot{m}_1$=10 kg/s, $\dot{m}_2$=1 kg/s, $T_1 = T_3$= 298.15 K, p_1 = 10 bar, p_2= 1 bar). To consider a wide spectrum of operating conditions, the heat transfer coefficient KA (kW/K) was varied from 0.1 to 40 kW/K.. The variation of ε and c_P versus KA are shown in Figs. 3-4, and Figs. 5-6, respectively.

As expected, if the SPECO approach is used, the exergetic efficiency increases and the cost of Product decreases when improving the behavior of the heat exchanger (i.e., for higher KA values). This is because the increase of exergy is assigned to the Product side, whereas the decrease of exergy to the Fuel side (Eq.7), and the latter occurs at constant cost per unit of exergy (see Eq. 8). Instead, using the DP approach the component behavior does not affect neither the exergetic efficiency nor the cost per unit of exergy of the Product, which remain constant. Thus, the DP definitions of Fuel and Product and the resulting exergetic efficiency and unit cost of product do not "detect" the improved behavior of the component deriving from higher KA values, although they are consistent with the exergetic balance of the component. This is because the "desired products" ($\dot{E}_2$ and $\dot{E}_4$) formulated by the DP approach are independent of the actual behavior of the component, which shows an exergy consumption on the hot side ($\dot{E}_1$-$\dot{E}_2$) that is used to increase the exergy on the cold side ($\dot{E}_4$-$\dot{E}_3$), as the SPECO approach simply records. In fact, when KA increases, T_2 decreases and T_4 increases and $\dot{E}_2$ and $\dot{E}_4$ show a similar trend, being $\dot{E}_1$ and $\dot{E}_3$ fixed at constant values by hypothesis. The two effects compensate so that the DP exergetic efficiency and cost per exergy unit of the product remain approximately constant.

Mixed streams

This second example consider the mixer of the two stage vapor-compression system in Fig. 7. Working fluid is ammonia (NH_3), cooling fluid in the condenser is water, heating fluid in the evaporator is a water-ethylene glycole mixture (50/50 %weight).

In the mixer the energy rejected during de-superheating and condensation of the refrigerant in the low temperature cycle is used to evaporate the refrigerant of the higher temperature cycle. Thus, as in the heat exchanger of the previous example, both cooling of the hot stream and heating of the cold stream are desired and useful (the mixer operates both as condenser and evaporator). The stream 6-3 gains exergy due to the condensation below the reference temperature, whereas the stream 2-7 loses exergy due to the evaporation below the reference temperature.

Accordingly, using the SPECO approach the exergy difference ($\dot{m}_3(e_3 - e_6)$) is positive (addition) and desired, and becomes part of the Product, whereas the exergy difference ($\dot{m}_2(e_2 - e_7)$) is negative (removal) and becomes part of the Fuel, i.e

$$\dot{E}_P = \dot{E}_3 - \dot{E}_6 \qquad \dot{E}_F = \dot{E}_2 - \dot{E}_7 \qquad \text{(SPECO)} \qquad (9)$$

Instead, using the DP approach, the output and input exergy streams are on the Product and Fuel sides, respectively

$$\dot{E}_P = \dot{E}_7 + \dot{E}_3 \qquad \dot{E}_F = \dot{E}_6 + \dot{E}_2 \qquad \text{(DP)} \qquad (10)$$

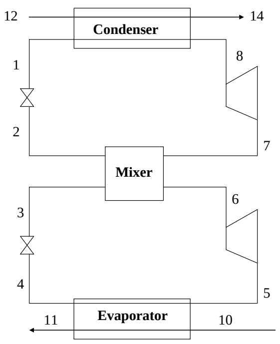

Figure 7: Two stage vapor-compression system

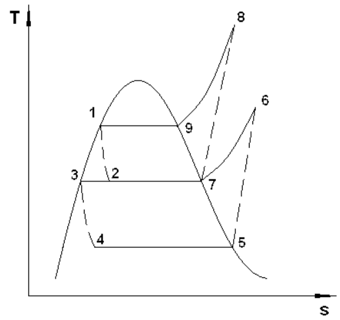

Figure 8: T-s diagram of the system in Fig.7

Thus, the exergy efficiencies of the mixer are

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{m}_6\left(e_3 - e_6\right)}{\dot{m}_2\left(e_2 - e_7\right)} \qquad \text{(SPECO)}$$

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{E}_7 + \dot{E}_3}{\dot{E}_6 + \dot{E}_2} \qquad \text{(DP)} \tag{11}$$

The cost balance of the mixer is

$$c_2\dot{E}_2 + c_6\dot{E}_6 = c_7\dot{E}_7 + c_3\dot{E}_3 + \dot{Z} \tag{12}$$

Amortization cost flow rates ($\dot{Z}$) are neglected here for simplicity as in the previous example. Specific costs c_2 and c_6 are known as they are calculated in the upstream components by the overall system model.

The F rule of the SPECO method applied to the exergy removal $\dot{m}_2\left(e_2 - e_7\right)$ (i.e to $\dot{E}_F$, see Eq.(9)) supplies the auxiliary equation

$$c_2 = c_7 \qquad \text{(SPECO)} \tag{13}$$

Using the DP approach the auxiliary equation is obtained by the P rule applied to the two terms of the component Product ($\dot{E}_7$ and $\dot{E}_3$)

$$c_3 = c_7 \qquad \text{(DP)} \tag{14}$$

According to the Product definitions in Eqs. (9) and (10) the costs per unit of exergy of the Products are

$$c_P = \frac{c_3\dot{E}_3 - c_6\dot{E}_6}{\dot{E}_3 - \dot{E}_6} \qquad \text{(SPECO)}$$

$$c_P = \frac{c_3\dot{E}_3 + c_7\dot{E}_7}{\dot{E}_3 + \dot{E}_7} = c_3 \qquad \text{(DP)} \tag{15}$$

The behavior of the mixer was simulated considering different values of the mixer pressure for two different temperatures of the water-ethylene glycole mixture at the inlet of the evaporator (T_{10} = -15°C, -30°C) and a fixed value of the heat transfer rate at the evaporator (10 kW). The water temperature at the inlet of the condenser was fixed at 25°C.

Results of the simulation are shown in Figures 9 to 12. The increase in the SPECO exergetic efficiency at increasing values of the mixer pressure (Fig. 9) is substantially due to the increasing value of T_6 which reduces the desired cooling of stream 6.

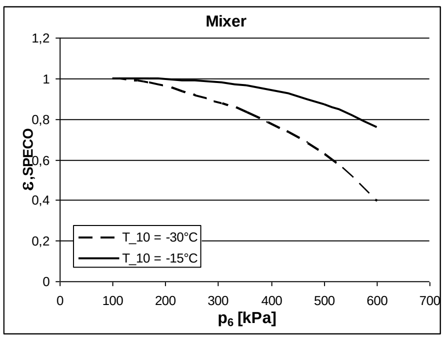

Figure 9: SPECO exergetic efficiency of the mixer in Fig.7.

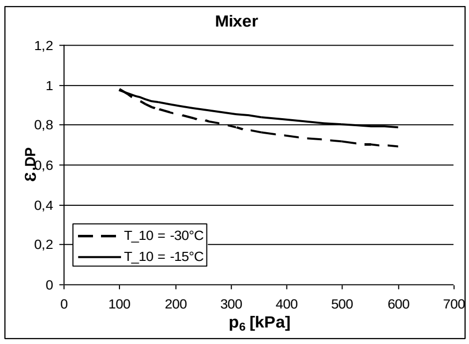

Figure 10: DP exergetic efficiency of the mixer in Fig.7.

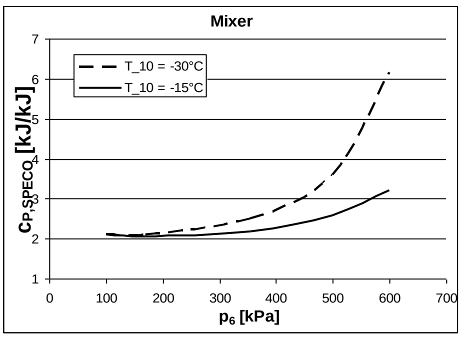

Figure 11: SPECO cost of product of the mixer in Fig.7.

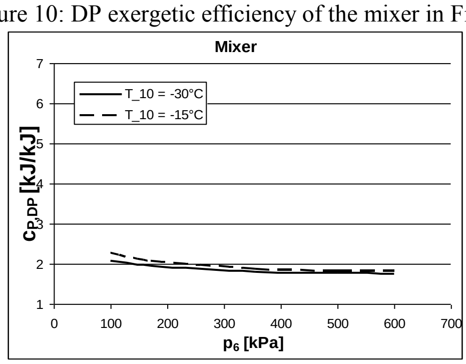

Figure 12: DP cost of product of the mixer in Fig.7.

The effect is more remarkable at T_{10}=-30°C. This worsening of the component behavior leads to the expected progressive increase in c_P (Fig. 10), which is more remarkable at T_{10}=-30°C as well. Instead, the DP exergetic efficiency decreases at increasing values of the mixer pressure (Fig. 11), and it is apparently not consistent with the worse component behavior. On the other hand, also c_P shows a decreasing (although smoother) trend (see Fig. 12), which does not appear to be consistent with the exergetic efficiency growth. So, also in this case the information deriving from ε and c_P does not seem useful in a design improvement procedure of the component in which improvements of the component behavior are expected to result in a higher exergetic efficiency and a lower c_P cost.

Cogeneration steam turbine

The last example considers the back-pressure steam turbine in Fig. 13 in which the steam at the exit is used for heating purposes.

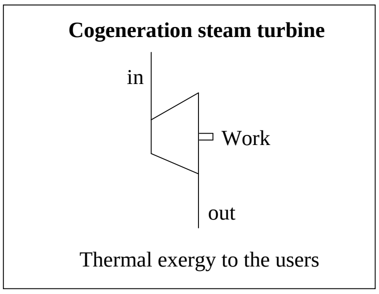

Figure 13: Cogeneration steam turbine.

According to the SPECO method the desired Product of the turbine is the shaft mechanical work, whereas the Fuel is equal to the exergy needed to generate the Product, i.e the removal of exergy from the steam crossing the turbine

$$\dot{E}_P = \dot{W} \qquad \dot{E}_F = \dot{E}_{in} - \dot{E}_{out} \quad \text{(SPECO)} \qquad (16)$$

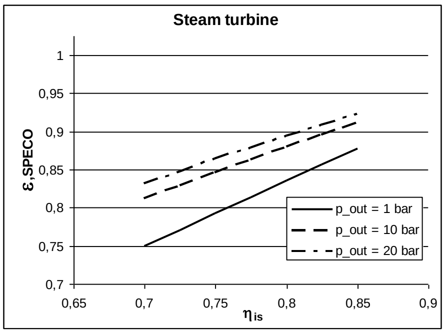

Figure14: SPECO exergetic efficiency of the steam turbine in Fig.13.

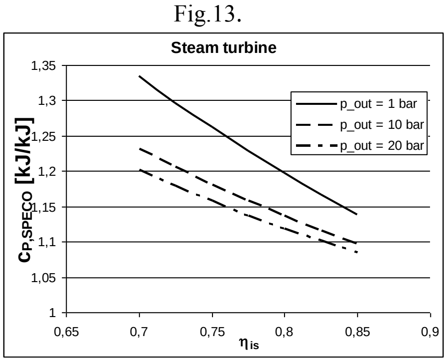

Figure 16: SPECO cost of product of the steam turbine in Fig.13.

Instead, using to the DP criterion both the thermal exergy and mechanical work at the outlet are considered as useful Products

$$\dot{E}_P = \dot{W} + \dot{E}_{out} \qquad \dot{E}_F = \dot{E}_{in} \qquad \text{(DP)} \qquad (17)$$

Thus, the SPECO and DP exergetic efficiencies are

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{W}}{\dot{E}_{in} + \dot{E}_{out}} \qquad \text{(SPECO)}$$

$$(18)$$

$$\varepsilon = \frac{\dot{E}_P}{\dot{E}_F} = \frac{\dot{W} + \dot{E}_{out}}{\dot{E}_{in}} \qquad \text{(DP)}$$

The cost balance of the component is

$$c_{in}\dot{E}_{in} = c_{out}\dot{E}_{out} + \dot{Z} \qquad (19)$$

Amortization cost flow rates ($\dot{Z}$) are neglected for simplicity as in the previous cases.

The F rule of the SPECO method applied to the exergy removal (Eq.12) supplies the auxiliary equation

$$c_{in} = c_{out} \qquad \text{(SPECO)} \qquad (20)$$

Using the DP approach the auxiliary equation is obtained by the P rule applied to the two terms of the component Product ($\dot{E}_7$ and $\dot{E}_3$)

$$c_W = c_{out} \qquad \text{(DP)} \qquad (21)$$

The costs per exergy unit of the Products are

$$c_P = c_W \qquad \text{(SPECO)}$$

$$(22)$$

$$c_P = \frac{c_{in}\dot{E}_{in}}{\dot{W} + \dot{E}_{out}} \qquad \text{(DP)}$$

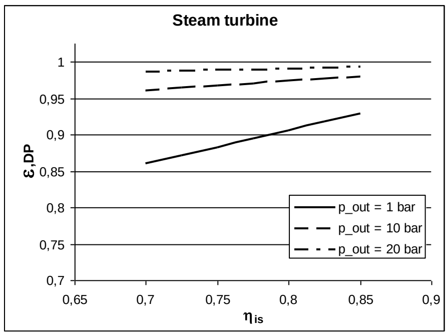

Figure 15: DP exergetic efficiency of the steam turbine in Fig.13.

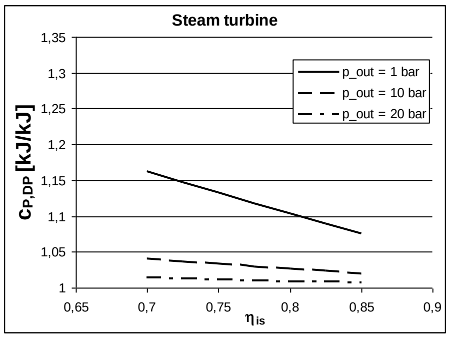

Figure 17: DP cost of product of the steam turbine in Fig.13.

The turbine behavior was modified by varying the isentropic efficiency in the range 0.7-0.85 at fixed inlet thermodynamic conditions (T_{in}=400°C, p_{in}=40bar) and for three values of the outlet pressure (p_{out}=1bar, 10bar, 20 bar). Results of the simulation are shown in Figures 9 to 12.

In this example both the SPECO and DP exergetic efficiencies increase as the isentropic efficiency increases. However, the rate of increase is higher for the SPECO formulation, and becomes very small for the DP one when p_{out} is closer to p_{in} (at =20 bar ε_{DP} is almost constant, see Fig.17). The cost per exergy unit of the Product shows a similar trend, which is almost flat for p_{out} 20 bar. In this latter case, as in all previous examples, the improvements of the component behavior are not detected by ε_{DP} and $c_{P,DP}$. This is because the definitions of these parameters places the "desired performance" of the users (that are stated according to the requirement of the users) before the real thermodynamic behavior of the component itself. So, the exergy stream at the output of the cogeneration turbine, which the turbine is not able to use, is considered as being generated in the same way of the mechanical work, and having the same exergetic (and monetary) value (per exergy unit) of the mechanical work at the turbine shaft. None of these two hypotheses corresponds to the real behavior of the turbine. The turbine "extracts" mechanical work from the steam flowing through it and leaves at the outlet some exergy which cannot be practically converted into mechanical work with 100% efficiency. So, its value cannot be the same as the value of the mechanical work.

CONCLUSIONS

The three examples presented in the paper show that components having a "double purpose" in the system in which they are included may suggest different Fuel and Product formulations, and consequently a different cost of Product. Two criteria were considered to formulate the Fuel and Product of these components:

- The SPECO one, which takes a record of all the exergy differences between inlet and outlet of the component and includes on the Product side the desired additions and on the Fuel side the exegy removals (consumption) needed to obtain the Product according to the actual component behavior;
- The so called Double Purpose approach, which states that input and output exergy streams belong to the Fuel and Product, respectively.

Both criteria are consistent with the exergy balance, but they supply very different values of the exergetic efficiency, and in turn of the cost of Product. The amplitude of these differences varies depending on the design features of the component. In particular, it is observed that the Double Purpose approach may lead to constant exergetic efficiency and constant exergetic cost of Product when the design behavior of the component is modified. This implies that improvements in the component design might not be "detected" by the exergetic efficiency and cost of Product, which may therefore become useless performance parameters in a design improvement procedure. This is because the definitions of these parameters given by the Double Purpose approach places the "desired performance" of the component (that are stated according to the requirement of the users) before the real thermodynamic behavior of the component itself. So, different forms of exergy that undergo different processes within the component may be considered as being generated in the same way and having the same value. Although this approach is "allowed" by exergoeconomics, it should in general be avoided when not dictated by the aggregation level of the system components. In this case (e.g., complex cogeneration plants that are considered as black-boxes having two or more products carrying different forms of exergy) it is necessary to consider the same cost for all the exergy units belonging to the different products. However, it is opinion of the author that the results of the analysis are strongly improved if the need of this approach is eliminated by considering a lower aggregation level of the component combined with the SPECO method.

ACKNOWLEDGMENT

Dr. Sergio Rech is gratefully acknowledged for helpful discussions and suggestions.

NOMENCLATURE

Symbol	Quantity	SI Unit
c	Specific monetary cost or Specific exergetic cost	\$/J J/J
e	Specific exergy	J/kg
$\dot{E}$	Exergy flow rate	J/s
KA	Heat transfer coefficient	W/K
$\dot{m}$	Mass flow rate	Kg/s
$\dot{Z}$	Amortization cost flo rate	\$/s

Subscripts

P	Associated with the Product of the component
F	Associated with the Fuel of the component

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