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A New Graphical Representation of the Exergy Balance

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The purpose of this paper is to present a new kind of diagram for representing exergy balance and supporting the engineer in his diagnosing step. The diagram relies on the computation of exergetic indicators (exergetic efficiency, irreversibility and exergy losses) of each unit operation making up the whole system. The use of the new graphical representation is illustrated through an example of a gas turbine.

1. Introduction

The Exergy concept, which results from the combination of the first and second laws of thermodynamics, has been proven to be an efficient tool for evaluating and improving energy efficiency of thermal and chemical processes (Gourmelon et al., In Press). However, the lack of a systematic procedure in examining and interpreting the results of the exergy balance makes this kind of analysis more or less limited to the academic world. Both the conventional and advanced exergy analysis relies on the computing of the exergy balance but also on the calculation of exergetic indicators such as the exergy efficiency. To help the engineer in defining unit operations of a process that should be improved as a priority, it is convenient to draw graphics such as pie graphs, bar charts or even Grassmann diagrams. However, these latters do not enable to represent in the same chart the amount of exergy lost/destroyed and exergy efficiency of each unit operations. Moreover the interpretation of all these indicators which is not so easy represents the major bottleneck to a widespread use of such a methodology. In order to make exergy analysis more understandable and to overcome some of the difficulties in industrial application, it was decided to develop a supporting graphical representation of the exergy analysis.

In this paper, the exergy concept is briefly explained. The new graphical representation is then presented and finally illustrated through a simple example of a gas turbine. This paper is based on the ProSimPlus® ‘ability to calculate exergy balances in a systematic way (ProSim S.A., 2014).

2. Exergy Concept

The exergy of a system (*B*) is defined as the maximum amount of work that can be obtained by bringing it to the equilibrium with the reference environment (Caballero et al., 2014; Szargut et al., 1988). Like energy, there are three kinds of exergy support: material streams, heat streams and work streams. Neglecting the kinetic and potential parts, the exergy of a material stream may be defined as the sum of chemical and physical exergy as expressed in Eq(1). Both terms may be computed as proposed by Gourmelon et al. (In Press). Work stream can be computed according to Eq(2). For diagnosis purpose, heat streams should be replaced by utility streams modeled with material streams.

$$B_{material} = B^{ph} + B^{ch} \tag{1}$$

$$B_{work} = W \tag{2}$$

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Using these equations the exergy balance of any system can be computed. Differently from mass or energy balances, an exergy balace contains a term *I* representing the thermodynamic imperfection also known as internal losses or irreversibility of the system (Tsatsaronis, 2007). To refine the exergy balance (Gong and Wall, 2001) proposed to make a distinction between waste and utilized streams. The exergy balance is then rewritten as expressed in Eq(3). Waste streams are streams that are directly released to the environment without specific use. $\mathrm{B_{in}}$, $\mathrm{B}_{\mathrm{out},utilized}$, B_{waste} and I represent the exergy input, utilized exergy output, external exergy losses and internal exergy losses, respectively.

$$B_{in} = B_{out,utilized} + I + B_{waste} \tag{3}$$

Another way to express the exergy balance of any system is given by Eq(4) where $\Delta\mathrm{B_{consumed}}$ is the amount of exergy consumed by the system, or fuel exergy, and $\Delta\mathrm{B_{produced}}$ is the amount of exergy produced, or product exergy (Tsatsaronis and Winhold, 1985).

$$\Delta B_{consumed} = \Delta B_{produced} + I + B_{waste} \tag{4}$$

Exergy Analysis, which is based on the simultaneous use of first and second laws of thermodynamics, has been shown to be a powerful tool for improving industrial processes as it enables to pinpoint thermodynamics imperfections and to compare different configurations. However, there is no graphical way for representing all the aspects of an exergy balance. To overcome this issue, this paper proposes a new kind of diagram based on Eq(4).

3. A new graphical representation

3.1 Definition of exergetic indicators

Three different indicators can be defined by rearranging Eq(4), providing the engineer with an estimate of the general usage of the exergy consumed by the system:

$$1 = \frac{\Delta B_{produced}}{\Delta B_{consumed}} + \frac{I}{\Delta B_{consumed}} + \frac{B_{waste}}{\Delta B_{consumed}} \tag{5}$$

First, the intrinsic efficiency (IE) is defined as the ratio of exergy produced to the exergy consumed (Eq(6)). Analogously the intrinsic irreversibility (II) and the intrinsic waste (IW) are defined according to Eq(7) and Eq(8), respectively.

$$IE = \frac{\Delta B_{produced}}{\Delta B_{consumed}} \tag{6}$$

$$II = \frac{I}{\Delta B_{consumed}} \tag{7}$$

$$IW = \frac{B_{waste}}{\Delta B_{consumed}} \tag{8}$$

3.2 Exergetic ternary diagram

Combining Eq(5) with Eq(6) to (8), we finally obtain Eq(9).

$$IE + II + IW = 1 \tag{9}$$

As a consequence, each unit operation may be represented by a point located inside a ternary diagram as represented in *Figure 1*.

As an example, let’s consider a unit operation represented by the point A in the figure 3.

- The intrinsic efficiency (IE) of the unit operation is equal to 30 %; this means that only 30 % of the consumed exergy has been used to produce utilized exergy.
- Its intrinsic irreversibility (II) is 60 %; this is the portion of the consumed exergy which is destroyed by the unit operation.
- Finally its intrinsic waste (IW) is 10 %; this means that 10 % of the consumed exergy is lost in waste streams.

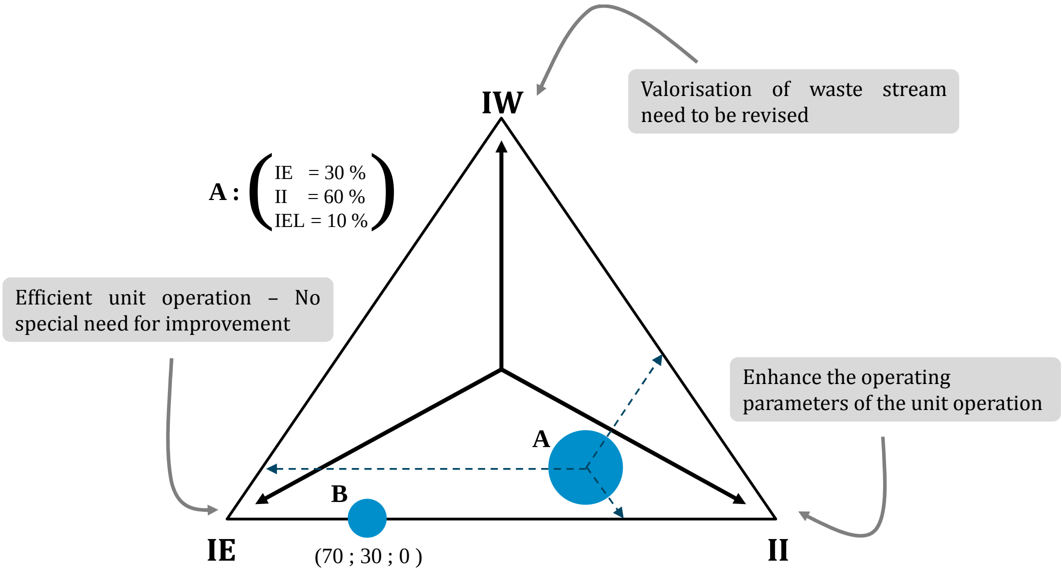

Figure 1: Exergetic ternary diagram

The point's position in the exergetic ternary diagram is a determinant for the improvement of a unit operation. First the engineer has to examine the position of the point referred to the vertex IE. The closer it is to this vertex, the more efficient the unit operation. Consequently the engineer would prefer to improve unit operations located far from this vertex. Then, for these operations, the engineer would prefer for instance to modify operating parameters to reduce internal losses (if the point is close to the vertex II) or to recover a waste stream to decrease the amount of external losses (if the point is close to the vertex IW).

Moreover, one has to consider the absolute value of the exergy loss. For that purpose, the point's size is proportional to the amount of exergy losses in the unit operation. For instance, unit operation A has a bigger exergy loss than point B. Let us take an example to illustrate the use of such a new graph.

4. Case study: Gas turbine with regeneration

4.1 Process description

The process shown in Figure 2 is a gas turbine system with regeneration. Air and Methane entering the gas turbine are compressed (C101 and C102), mixed (M101) and sent to the combustion chamber R101. Flue gases are expanded down to 1 atm in the turbine T101 to produce shaft-work. Air stream is preheated thanks to the flue gases.

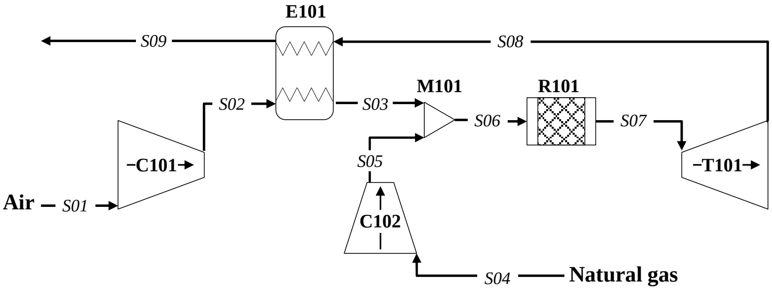

Figure 2: Gas-turbine system

4.2 Exergy-based diagnosis

Exergy Analysis is used as diagnosis tool to examine the case study. Irreversibility, amounts of external losses and exergy indicators as defined in paragraph 3.1 have been calculated with the ProSimPlus® modeling and simulation environment (ProSim S.A., 2014). Results are graphically represented in the exergetic ternary diagram in Figure 3. Exergy balances are summarized in Table 1.

Table 1: Mass and exergy balance of gas turbine

Streams		S01	S02	S03	S04	S05	S06	S07	S08	S09
Flow rate (kmol/h)		623.91	623.91	623.91	13.35	13.35	637.26	637.26	637.26	637.26
Molar fractions	CH_4	0.00	0.00	0.00	1.00	1.00	0.02	0.00	0.00	0.00
	O_2	0.21	0.21	0.21	0.00	0.00	0.21	0.16	0.16	0.16
	N_2	0.79	0.79	0.79	0.00	0.00	0.77	0.77	0.77	0.77
	H_2O	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.04	0.04
	CO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02
Temperature (K)		298.15	560.81	600.00	298.15	475.56	595.88	1,106.21	852.71	817.07
Pressure (atm)		1.00	5.51	5.25	1.00	5.25	5.25	5.00	1.00	0.97
Physical Exergy (MW)		0.00	1,117.33	1,197.04	0.00	21.08	1,216.84	3,099.85	1,341.26	1,194.95
Chemical exergy (MW)		13.52	13.52	13.52	3,085.82	3,085.82	3,054.69	37.34	37.34	37.34
Total exergy (MW)		13.52	1,130.85	1,210.56	3,085.82	3,106.90	4,271.53	3,137.19	1,378.59	1,232.29

As it can be seen in Figure 3, the mixer M101 has a relatively low exergy loss compared to the whole process. Such an internal loss is mainly due to non-homogeneities in temperature, pressure and/or chemical composition of mixed streams (Le Goff, 1979). One solution to reduce the amount of exergy destroyed might be to mix as isothermal and isobar as possible. However in our case, this loss is neglected.

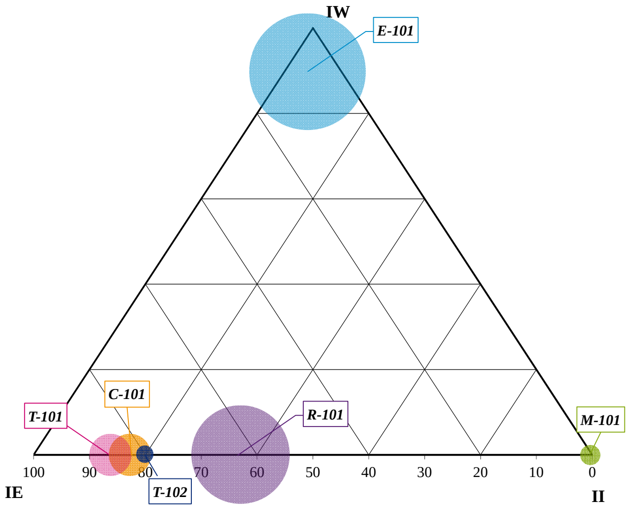

Figure 3: Exergetic ternary diagram of the case study (S03 Temperature at 600 K)

According to the Figure 3, among the amount of exergy consumed in the heat exchanger E101, approximately 5% is destroyed while a higher amount of exergy, almost 90 %, is lost in the waste stream. As it can be seen in Figure 4, most of the lost exergy is the physical exergy. One way to reduce such a loss is to bring the stream as close as possible to the environment conditions in terms of pressure and temperature. In this case, one needs to decrease the temperature of the waste stream. The temperature based exergy might be recovered to heat another cold stream.

The chemical reactor R101 is simulating a combustion chamber as an adiabatic reactor. Figure 3 clearly shows that R101 is the main source of internal losses in the whole process. Here most of the internal losses are due to chemical reaction. Nevertheless several authors (Cziesla et al., 2006; Hagi et al., 2013) proposed to increase the preheating temperature. This solution could be generalized to all exothermic reactions: raising the input temperature enables to decrease the amount of exergy destroyed. Concerning turbines and compressors, irreversibilities are caused by the dissipative effects. Both kinds of unit operation are simulated with a given isentropic efficiency. However reduction of internal losses can be obtained by modifying inlet streams characteristics such as temperature or pressure. For a compressor, the lower is the inlet temperature the lower is the amount of exergy destroyed. Regarding the turbine, the higher the input temperature the lower irreversibilities.

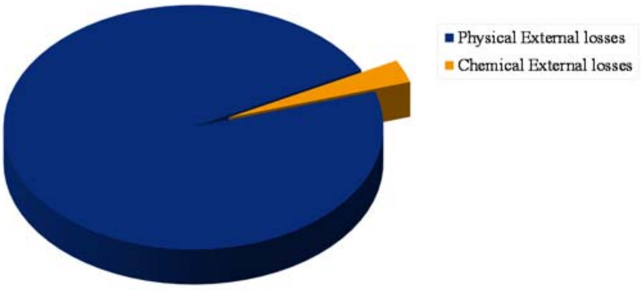

Figure 4: Exergy components distribution of the waste stream

4.3 Proposal for improvement

Figure 3 clearly identifies chemical R101 as the major source of irreversibilities and heat exchanger E101 as the lonely but relatively high source of waste stream. As mentioned by Tsatsaronis (1993), the reduction of such sources of inefficiencies can be achieved, for instance, by increasing the air preheating temperature (stream S03). Such a modification will decrease the waste temperature thus reducing the amount of exergy lost, but also improve the combustion chamber efficiency. Two temperatures have been chosen (700 and 900 K) and the new exergetic ternary diagram has been drawn for both temperature in Figure 5 and Figure 6, respectively.

From the two last figures, one may notice that E101 and R101 remain the main sources of thermodynamic imperfection of the process. Nevertheless, one may note that points representing R101 and E101 have moved closer to IE tip of the exergetic ternary diagram. Moreover increasing the air preheating temperature has also a positive impact on the turbine T101. The temperature of output gas from the combustion chamber has also risen due to the increase of input temperature, then reducing the amount of exergy destroyed by the turbine. This means that the exergy is consumed in a more efficient way.

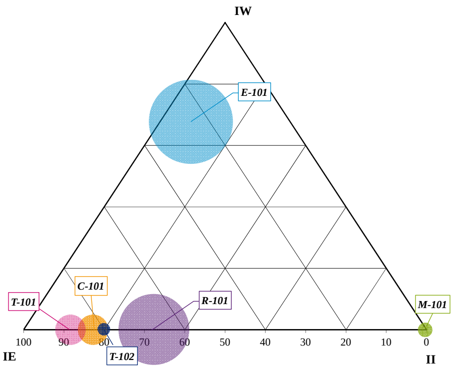

Figure 5: Exergetic ternary diagram for S03 at 700 K

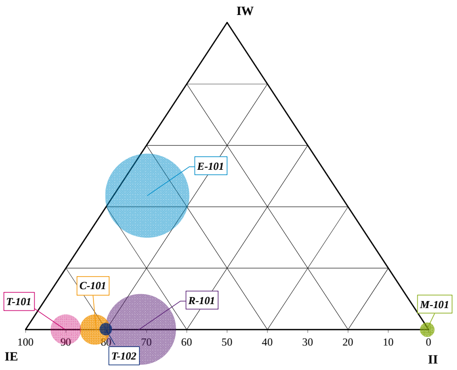

Figure 6: Exergetic ternary diagram for S03 at 900 K

5. Conclusion

This paper aims at presenting a new kind of diagram, the exergetic ternary diagram, for helping engineers in the diagnosing step. The illustration of its use in the example of a gas turbine with regeneration clearly shows its usefulness. Notice that such a graph may be use as graphical tool for parametric optimization. The more efficient the process, the closer to IE vertex the unit operations are in the diagram. Nevertheless, this graph could still be improved by taking into account the avoidable irreversibility instead of total irreversibility (Açıkkalp et al., 2014; Boyano et al., 2012; Feng et al., 1996). This would enable to calculate the true potential for improvement of unit operations (Tsatsaronis and Park, 2002).

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