

7.2.2 EXERGY BALANCES

Exergy depends on both the system state and the chemical composition of its elements. It differs from energy in that the latter is preserved while exergy is destroyed whenever irreversibilities exist. Since it is not a conservative quantity, equation (7.2.1) cannot be applied and a specific approach should be used.

Let us recall some results established in section 2.5. For an open multitherm system in steady-state traversed by a constant flow of fluid, which exchanges work and heat with n external sources at constant temperatures T_k , and the environment at temperature T_0 , the exergy equation (2.5. 3) can be rewritten as:

$$\Delta x_{hi} = \tau - \Delta x_h + \sum_{k=1}^n x_{qk} \quad (7.2.2)$$

Δx_{hi} represents the exergy dissipation resulting from irreversibilities, τ the work received by the system, Δx_h the exergy variation of the fluid passing through it, $x_{qk} = \theta_k Q_k$ the heat-exergy or useful heat received from source at temperature T_k , $\theta_k = 1 - T_0/T_k$ being called the Carnot factor.

Equation (7.2.2) shows that the maximum work that an open system can provide is equal to the sum of heat-exergies of sources with which it exchanges heat, minus the change in exergy of the fluid passing through it and the exergy destroyed due to irreversibilities.

When the heat sources are no longer at constant temperature, when several shaft systems must be considered and the system is crossed by several fluids, equation (7.2.2) must be replaced by a more complicated one.

To calculate irreversibilities of each component j , it becomes (7.2.3):

$$\Delta x_{hij} = \sum_{k=1}^n x_{qjk} - m_j \Delta x_{hj} + \tau_j \quad (7.2.3)$$

If the heat exchange takes place at variable temperature:

$$x_{qk} = \int_{T_a}^{T_b} \left(1 - \frac{T_0}{T_k}\right) \delta Q_k \quad (7.2.4)$$

Assuming a linear variation of heat exchange function of T :

$$x_{qk} = \left(1 - \frac{T_0}{T_b - T_a} \ln \left(\frac{T_b}{T_a}\right)\right) Q_k$$

To calculate irreversibilities in a heat exchanger, simply add equations member by member (7.2.3) related to each fluid flowing through it. If it is adiabatic (no heat losses with the surroundings) heat-exergies are zero. As the useful work is zero, the irreversibility is equal to the sum of exergy variations of both fluids.

In section 2.5.5 we introduced the exergy efficiency of a system, always between 0 and 1, and higher than the irreversibilities are low. It is defined as the ratio of exergy

uses to exergy resources. Exergy resources are the sum of all exergies that we had to provide to the cycle from outside. Exergy uses represents the net balance of the cycle, i.e. the algebraic sum of exergies produced and consumed within it.

If the system consists of components satisfying equation (7.2.3), this general definition is mathematically translated by equation (7.2.5):

$$\eta_x = 1 - \frac{\Sigma (\Delta x_{hij})}{\Sigma (\Delta x_{qj}^+) + \Sigma (\tau_j^+)} \quad (7.2.5)$$

The denominator represents the exergy provided, i.e. the sum of positive heat-exergies and useful work provided to the cycle. The numerator is the sum of the cycle irreversibilities.

7.2.3 PRACTICAL IMPLEMENTATION IN A SPREADSHEET

For simple cycles, establishing an exergy balance poses no particular difficulty but needs to be done very carefully otherwise errors can be committed.

To facilitate this task, a spreadsheet, named BilansExerThopt.xls has been prepared for you. Downloadable from the Thermoptim-UNIT portal¹, it gathers a number of worksheets related to the examples illustrating Thermoptim use. It is complemented by a detailed methodological note which explains how to reuse Thermoptim result files.

In addition, the Diapason e-learning module S06, which deals specifically with exergy balances, will guide you through your first steps, and modules S23, S28 and S32 will help you build the exergy balance of a gas turbine, a steam plant or a vapor compression refrigeration machine.

In practical terms, and although the procedure is not yet automated within the package, the exergy balance of a cycle can be established in the following manner when it is modeled in Thermoptim:

- once the model is properly set and calculated (it is not actually enough to load a project and export its results: as the exergies are not saved in project files, they must be recalculated for each component) the results file can be exported (line "Export Results" menu "Results File"). This is a text file that can easily be read in a spreadsheet, and in which different values are calculated for a number of point state functions (intensive variables) and the energy and exergy involved in processes;
- the first lines of this file can be copied into a spreadsheet prepared before. You should take care that the spreadsheet does not always recognize the thousands separator, and it may be necessary to make a global suppression of that separator (for this, copy the separator, select "Delete" from the menu "Edit" of the spreadsheet, paste the separator in the search field without putting anything in the replacement field, and then click " Replace All");
- you must then carefully correct by hand the part of the worksheet that makes the exergy balance, as the lines for the different processes should be constructed differently (see below equations 6 and 7) depending on whether they relate to

¹ <http://www.thermoptim.org/sections/base-methodologique/analyses-exergetiques/analyse->

adiabatic expansion or compression or heat exchanges with the outside. For the latter, you must also specify the value of the source temperature. Finally, you should take into account in $\Sigma (\tau_j^+)$ the powers supplied to the system from outside;

- if you only have the demo version of ThermoOptim you must slightly modify the spreadsheet to recalculate the exergies brought into play in the processes from the values calculated in the points screens and from the flow-rates involved, which must be copied one by one.

For simple processes, through which flows a fluid flow-rate m , equation (7.2.2) is rewritten as appropriate:

- for adiabatic processes ($Q = 0$, $\tau = m\Delta h$)

$$\Delta x_{hi} = m\Delta h - m\Delta x_h \quad (7.2.6)$$

- for processes without work and with heat exchange with a source at temperature T ($\tau = 0$, $Q = m\Delta h$)

$$\Delta x_{hi} = m\Delta x_h + \left(1 - \frac{T_0}{T}\right)m\Delta h \quad (7.2.7)$$

économiseur	B	3a	échange	1126.84604	494.901154	payante		1
prélèvement	4a	4a	échange	0	0	autre	0.15	
resurchauffe	4a	3c	échange	466.171557	275.380302	payante	0.85	
surchauffeur	3b	3	échange	890.820093	523.336681	payante		1
vaporiseur	3a	3b	échange	898.274438	482.723771	payante		1
bilan enthalpique				bilan exergetique				
évolution	dh	τ	Q	Tk	dxq	dxh	dxhi	% pertes globales
compression liq 2	15	15				14	0	0.01%
compression liquide	2	2				3	0	-0.01%
turbine HP	-417	-417				-454	37	2.74%
turbine BP	-1030	-1030				-1209	179	13.32%
condenseur	-1952		-1952	288.15	0	-32	32	2.36%
économiseur	1127		1127	1600	924	495	429	31.95%
prélèvement	0		0			0	0	0.00%
resurchauffe	466		466	1600	382	275	107	7.96%
surchauffeur	891		891	1600	730	523	207	15.42%
vaporiseur	898		898	1600	737	483	254	18.90%
mélangeur						-99	99	7.35%
cycle	0	-1430	1430			0	1343	100.0%
						sigma(xq+)	2773	
						sigma(tau+)	0.00	
rendement energetique		42.29%	rendement exergetique		51.58%			

Figure 7.2.1: Exergy balance of a reheat and extraction steam cycle

On the worksheet in Figure 7.2.1, the ThermoOptim result file appears in the upper part, and in the bottom the lines that need to be corrected. The connection between the lower and upper is made by the cell formulas, those in red should not be modified, except in special cases discussed below in italics, while those in blue correspond to the mechanical power put into play, and those in black to heat exchange with outside sources. The important thing to check is first that each line applies to a suitable component (the order of processes in ThermoOptim file is unpredictable because it depends on that of their creation), and second the temperatures T_k are entered correctly. You should correct line by line the balance calculation by copying and pasting. Note in the example of Figure 7.2.1 that appears a process-point ("extraction") that obviously does not participate in the exergy balance. We can remove it if desired, first from the lower and then from the upper part to avoid losing references and formulas.

In addition to this formatting of the bottom of the spreadsheet, it may be necessary to perform a number of changes, depending on the case treated. They are listed below.

First, mixers not being processes in ThermoOptim, they are not automatically included in the exergy balance of this worksheet. It is therefore necessary to add them by hand, equation (7.2.3) including only the variation of exergy within the component, since the mixer is adiabatic and without work.

enthalpy balance				exergy balance				
component	dh	τ	Q	Tk	dxq	dxh	dxhi	% overall losses
compressor	443	443				402	40	7%
turbine	-761	-761				-796	35	6%
combustion chamber	890		890		890	619	270	47%
intake / exhaust						-225	225	39%
cycle	571	-318	890			0	571	100%
				$\sigma(xq+)$		890		
				$\sigma(\tau+)$		0.00		
energy efficiency		35.77%		exergy efficiency		36%		

Figure 7.2.2: Exergy balance of a simple gas turbine

For the combustion chambers, heat-exergy is replaced by the fuel exergy input. According to the authors, the literature indicates that the exergy of a fuel is close to its LHV or its HHV. These two values differing little, and given the fact that we seek to establish an approximate balance, we will follow those who equate it with its LHV available in ThermoOptim.

enthalpy balance				exergy balance				
component	dh	τ	Q	Tk	dxq	dxh	dxhi	% overall losses
HRSG 3	-101		-101			-50	15	5.96%
economizer	101		101			35		0.00%
HRSG 2	-91		-91			-57	10	3.80%
vaporizer	91		91			47		0.00%
HRSG 1	-52		-52			-37	8	2.93%
superheater	52		52			29		0.00%
feedwater pump	1	1				1	0	0.00%
turbine	-91	-91				-107	16	6.09%
condenser	-154		-154	288.15		-5	5	1.83%
air compressor	243	243				221	22	8.66%
gas turbine	-376	-376				-394	19	7.36%
combustion chamber	466		466		466	323	143	55.75%
intake / exhaust						-20	20	7.63%
cycle	90	-223	312			12	257	100%
				$\sigma(xq+)$		466		
				$\sigma(\tau+)$		0.00		
energy efficiency		47.76%		exergy efficiency		45%		

Figure 7.2.3: Exergy balance of a single pressure combined cycle

Another special case is non-closed cycles, in which the exergy entering the cycle and leaving it must be taken into account. The calculation of Δx_h must then be amended.

The example of the simple gas turbine given Figure 7.2.2 illustrates these two points. Here, the exergy entering and leaving the cycle is taken into account thanks to an extra line called "intake/exhaust". It represents a very significant part of losses. When there is internal heat exchange, as is the case in combined cycles, the calculation of the exergy loss also needs to be amended as discussed above: it is equal in absolute value to the algebraic sum of the changes of exergy of the two fluids which exchange heat. Since there is internal exchange, it is obviously useless to calculate the related heat-exergy.

If you want to know the details of losses in the different internal exchangers, it is necessary to change the Δx_{hi} formula for fluids brought into play, by coupling the

corresponding lines. If we simply make an overall balance, just sum up the overall exergy variation of all fluids.

For example, for the single pressure combined cycle of Figure 7.2.3, the following lines must be matched: lines 42 and 48 corresponding to the economizer, 43 and 50 to the vaporizer and 44 and 49 to the superheater. For clarity, it is of course possible to change the order of lines in the lower and higher parts of the worksheet so that the fluids matched are displayed together.