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Adrien Gomez, Catherine Azzaro-Pantel, Serge Domenech, Luc Pibouleau, Christian Latgé, et al.. Exergy analysis for Generation IV nuclear plant optimization. *International Journal of Energy Research*, 2010, 34 (7), pp.609-625. 10.1002/er.1575 . hal-03474782

HAL Id: hal-03474782

<https://hal.science/hal-03474782>

Submitted on 10 Dec 2021

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URL : <http://dx.doi.org/10.1002/er.1575>

To cite this version : Azzaro-Pantel, Catherine and Dumaz, Patrick and Domenech, Serge and Gomez, Adrien and Haubensack, David and Latgé, Christian and Pibouleau, Luc (2009) [*Exergy analysis for Generation IV nuclear plant optimization*](#). International Journal of Energy Research . ISSN 0363-907X

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Exergy analysis for Generation IV nuclear plant optimization

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Abstract

This article deals to the application of exergy concept to the energy production system involving a VHTR (Very High Temperature Reactor) coupled with an innovative electricity-generating cycle. The objective is to propose a general formulation to quantify the exergy destruction of the involved process components embedded in a thermodynamic simulator CYCLOP (Haubensack, 2004). The exergy destruction is thus identified as a major criterion to minimize. For this purpose, a genetic algorithm embedded in the so-called MULTIGEN environment is used. Finally, the optimization criterion, based on exergy destruction minimization, is applied to electrical production by a Brayton-Rankine combined cycle connected to a nuclear reactor. Some typical results are presented. The perspectives of this work including the cogeneration of hydrogen and electricity are highlighted.

Keywords: exergy analysis, general formulation, thermodynamic simulator, CYCLOP, optimization criteria, generating cycles, genetic algorithm

1. Introduction

Whatever the energy conversion system studied, the “delivered work” constitutes the “convertible” amount of the primary energy supplied to the system, referred as exergy. This approach, based on the simultaneous application of first and second law of thermodynamics, has received a renewed interest in analysis and design of electricity production and management (Becerra-Lopez et al., 2007; Borelli et al., 2008), chemical processes (Rosen, 2008; Suphanit, 2007) and cogeneration plants (Gomez et al., 2007; Ertesvag, 2007; Tsatsaronis, 2008; Kanoglu, 2009; Abusoglu, 2009; Sayyaadi, 2008).

Exergy, first called “useful energy” or “energy which can be mechanized” (Scott, 2003) originated in the field of the steam engines (pistons, turbines). A major advantage of the exergy concept is that it integrates not only a quantitative but also a qualitative consideration of irreversibility sources in an energy conversion process. Irreversibility implies exergy destruction and, by extension, potential to harm the environment. Exergy is in fact the maximum fraction of the total energy that can be extracted to produce a work.

Nature has three principal modes for exergy storage (Scott, 2003): mechanical non-equilibrium (gravitational potential, kinetic and pressure differences); thermal non-

equilibrium (temperature differences); chemical non-equilibrium (including electrochemistry) non-equilibrium. Electromagnetism can be viewed as another mode of storage, but is relatively marginal in terms of quantity, as compared with the others.

The energy production system considered in this study involves a VHTR (Very High Temperature Reactor) concept, considered as the nearest-term reactor design. It can indeed be coupled on the one hand, with innovative electricity-generating cycles and, on the other hand, with massive H₂ production processes. Thus, due to a high exit core temperature (at least 950°C) reached by helium used for cooling, VHTR is dedicated to the cogeneration of electricity and hydrogen by Sulphur-Iodine (S-I) thermochemical cycle or by High Temperature Electrolysis of steam water. Globally, these processes require the simultaneous supply of electricity and heat at high temperature. The optimal design of these process configurations constitutes an important challenge and a general optimization criterion is needed.

In this paper, only the section devoted to electricity production is considered. For this purpose, a model based on exergy theory is developed for the studied energy conversion system, in order to evaluate the exergy destruction level of process components embedded in a thermodynamic simulator CYCLOP (Haubensack, 2004): the main principles of this simulator are described briefly in Section 2. CYCLOP models several components (turbines, heat exchangers ...) for which it is necessary to compute exergetic efficiency. The following part of this article deals with the exergetic balance for a general component, which represents the first step before exergy integration within CYCLOP simulator. Since each simulator has its own modelling language, with an associated formalism, it is necessary to adapt the rigorous exergy balance expression to its particular context: the adaptation in CYCLOP will be the core of Section 4, taking into account both exergy destruction on components and during exergy transfer between them. The result of this work leads to quantify the destruction of exergy, that will constitute in turn the adopted optimization criterion.

Finally, the optimization criterion, based on exergy destruction minimization, is applied to electrical production by the combined cycle connected to a nuclear reactor. The perspectives of this work including the cogeneration of hydrogen and electricity will be highlighted.

2. Principles of CYCLOP simulation tool

For the particular case of future Generation IV nuclear reactors, it is necessary to describe, study and optimize any power conversion cycle, and to compare several cycles based on the same core.

The so-called CYCLOP (Haubensack, 2004) simulator allows a user to model a power conversion system in its globality and to study the respective influence of any components characteristics or cycle thermodynamical points on the global net efficiency of the cycle (or any other global parameter that should be optimized).

CYCLOP (for CYCLE OPTimization) is a computer tool implementing an automatic resolution of mass and energy balances of any reactor (first law of thermodynamics). A reactor is designed as a set of fluid loops built out of energetic components connected together (figure 1) by thermodynamical points and exchanging energy through calorific, mechanical or electrical transfers. Several fluids are available: gas like helium and nitrogen, but also two-phase fluids like water or carbon dioxide (from liquid to supercritical domains). Gas mixtures are also possible. Various components are available, like reactor cores, turbines, pumps, compressors, heat exchangers, alternators, steam generators, water condensers, dryers, etc... Each component is described by macroscopic parameters like isentropic efficiency, pressure

loss, calorific loss, mechanical or energetic efficiency that implements the second principle of thermodynamics.

Figure 1 represents the Brayton cycle using CYCLOP formalism. The components are connected by energy flows: energy flows can present losses. Therefore, it is necessary to consider simultaneously exergy destruction on components and exergy loss during energy transfer. The objective of the following sections is to introduce the theory of the exergy, as a tool for effectiveness analysis, and as an optimization criterion for the systems modelled with CYCLOP.

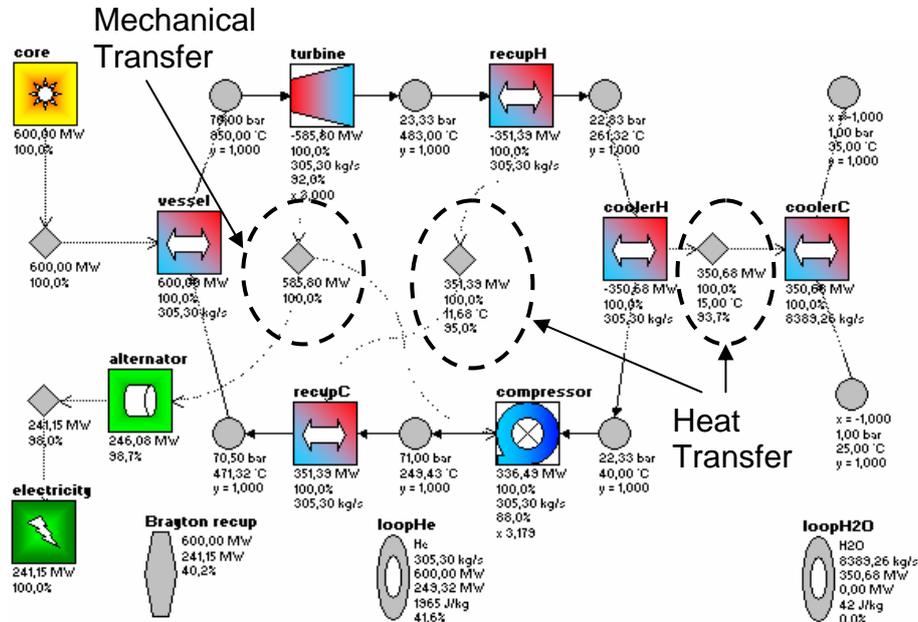


Figure 1 – Flowsheet of the Brayton cycle with CYCLOP

3. Exergy balance for a system with no chemical reaction

The first step consists in carrying out an exergy balance for CYCLOP components in order to derive a general expression for an automatic computation within CYCLOP.

The interest of any conversion system of energy is to exploit the maximal available amount of “useful” energy (heat at various temperatures, electrical energy, mechanics...).

The concept of usable energy was initiated by Carnot but concretely described by George-Louis Gouy in 1889 (Gouy, 1889). The potentiality of a system, from the point of view of the production of work, can be expressed by a function traducing not only the internal energy of the system, but also the temperature and pressure of the external atmosphere (25°C, 1 atm) of the system.

If the first and second principles are applied to a simple system, as represented in Figure 2, it can be seen as an open system receiving heat from various hot sources, exchanging heat with the atmosphere and producing energy with various forms (heat with T_s mean temperature, electricity, mechanical energy).

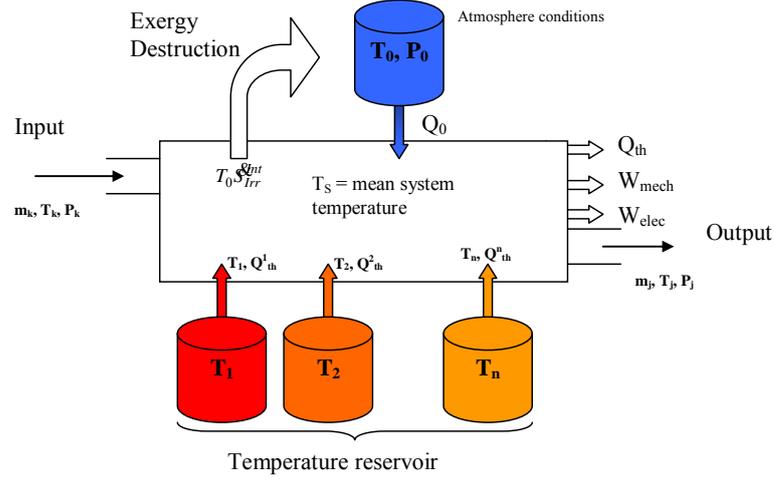


Figure 2 – Exergetic model of a general thermodynamic machine.

By respecting the conventional signs of thermodynamic flows (positive value for received energy, negative for transferred energy or losses) and neglecting kinetic and potential energy of inlet and outlet flows, the enthalpy balance is expressed as:

$$0 = -Q_{th} - W_{mech} - W_{elec} - \left[\sum_{j=1}^{NI} m_j \cdot h_j \right]_{out} + \left[\sum_{k=1}^{NO} m_k \cdot h_k \right]_{in} + \sum_{i=1}^{NHS} Q_{th}^i + Q_0 \quad (2)$$

The entropy balance can be written as follows:

$$0 = - \sum_{i=1}^{NHS} \frac{Q_{th}^i}{T_i} - \frac{Q_0}{T_0} + \frac{Q_{th}}{T_s} + \left[\sum_{j=1}^{NO} m_j \cdot s_j \right]_{out} - \left[\sum_{k=1}^{NI} m_k \cdot s_k \right]_{in} - \dot{S}_{gen} \quad (3)$$

Generally, the atmospheric energy contribution and its associated entropic flow are equal to zero, according to the principle of (Gouy, 1889).

Eliminating Q_0 between Equations (2) and (3), we obtain:

$$0 = -Q_{th} \cdot \left(1 - \frac{T_0}{T_s} \right) - W_{mech} - W_{elec} + \sum_{i=1}^{NHS} Q_{th}^i \cdot \left(1 - \frac{T_0}{T_i} \right) - \left[\sum_{k=1}^{NO} m_k \cdot (h_k - T_0 \cdot s_k) \right]_{in} + \left[\sum_{j=1}^{NI} m_j \cdot (h_j - T_0 \cdot s_j) \right]_{out} - T_0 \cdot \dot{S}_{gen} \quad (4)$$

Equation (4) must be written from exergy production point of view, as:

$$Q_{th} \cdot \left(1 - \frac{T_0}{T_s}\right) + W_{mech} + W_{elec} = \left[\sum_{i=1}^{NHS} Q_{th}^i \cdot \left(1 - \frac{T_0}{T_i}\right) + \sum_{k=1}^{NI} m_k \cdot (h_k - T_0 \cdot s_k) \right]_{in} - \left[\sum_{k=1}^{NO} m_j \cdot (h_j - T_0 \cdot s_j) \right]_{out} - T_0 \cdot \dot{s}_{gen} \quad (5)$$

For the input and output mass flows, the associated exergy terms can be defined:

$$e_k = h_k - T_0 \cdot s_k \quad (6)$$

This equation is generally identified (Borel, 1984; Bejan, 1984) as the exergetic balance expression for a given open system. Equation (5) is written here in the direction of energy production (thermal, mechanical and electrical) but the equation remains true whatever the case (system supplied with mechanical or electrical energy) since a formal limitation does not exist. Each term can be computed since the system is known.

From a thermodynamic point of view, the exergetic balance expression contains more information on the system, compared to an enthalpy assessment, and makes it possible to compare the various kinds of power with a common basis.

From the analysis of Equation (5), additional concepts can be pointed out:

- Both mechanical and electrical energies are considered as pure exergy terms.
- Thermal energy is considered as degraded by a Carnot factor, in its form of exergy, according to the associated temperature with the supplied power.
- The mass flows can represent a source and a loss of energy for the studied system. The computation procedure of the average system temperature will be presented in section (4.4).
- The entropy generation, that is equivalent to exergy destruction, must be minimized in order to maximize exergy production.

Equation (5) does not take into account the thermal losses towards the outside: this point will be investigated in section (4.3).

This balance applies to any type of component, (exchanger, compressor,...) in a local way, but can also be used globally at the process limits: it is particularly the case of heat release to the outside (cooling towers for instance). This formulation must be yet adapted to CYCLOP formalism to deduce the expression of the final optimization criterion.

4. Formulation of exergy-based criteria

This section is devoted to the application of exergy and to the computation of exergy destruction implemented in CYCLOP simulator (Haubensack, 2004).

For all the following equations, we take into account a particular formalism that may differ from the classical thermodynamics convention. This formalism is justified by the implementation of exergy balance in CYCLOP source code. First, the rigorous exergetic

balance must be adapted to calculate exergy destruction level, but the main objective of this part is to clarify several particular cases generated by CYCLOP formalism.

For heat transfer, the definition of temperatures associated with these flows depends on the operating conditions of each component. The thermal losses due to cooling loops must be taken into account since input flows and conditions are fixed. From a general point of view, exergy losses during energy transfer between components are modelled. Finally, a general procedure to check the automatic computation is proposed.

4.1. General exergy destruction model

Here, the assumptions and limitations of the energy criterion, based on exergy destruction, are presented.

4.1.1 Internal irreversibility of a component

At a component level, a thermodynamic machine is assumed to have:

- Several input/output mass flows;
- Several input thermal sources;
- Several input/output of electricity or mechanical energy.

The transformations within the component then induce losses of exergy (internal irreversibilities) which must be minimized. The exergetic balance can be presented in the form of three equations, taking into account the abovementioned input/output flows:

- A balance on mass flows,

$$T_0 \dot{S}_{gen}^{flow} = \sum_i m_i \times [(h - T_0 s)(T_{In}^i, P_{In}^i)] - \sum_j m_j \times [(h - T_0 s)(T_{Out}^j, P_{Out}^j)] \quad (7)$$

- A balance on the electrical/mechanical outputs (pure exergy),

$$T_0 \dot{S}_{gen}^{elec/mech} = \sum_k W_{Rec}^k - \sum_l W_{Trans}^l - W_{Loss} \quad (8)$$

- A balance on thermal power,

$$T_0 \dot{S}_{gen}^{Th} = \sum_k W_{Rec}^k \times \left(1 - \frac{T_0}{T_k}\right) - \sum_l W_{Trans}^l \times \left(1 - \frac{T_0}{T_s}\right) - W_{Loss} \times \left(1 - \frac{T_0}{T_s}\right) \quad (9)$$

- The internal energy of the system is already calculated by CYCLOP and is expressed by:

$$W_{Int} = \sum_j m_j \times h(T_{Out}^j, P_{Out}^j) - \sum_i m_i \times h(T_{In}^i, P_{In}^i) \quad (10)$$

The irreversibility balance for the system makes it possible to write Equation (11). The quantity “W” represents the exchanged power whatever the energy is.

$$T_0 \dot{S}_{gen}^{Total} = -W_{Int} + T_0 \times \left[\sum_i m_i \times s(T_{In}^i, P_{In}^i) - \sum_j m_j \times s(T_{Out}^j, P_{Out}^j) \right] + \sum_k W_{Rec}^k \times \delta_{Rec}^k(T_k) - \sum_l W_{Trans}^l \times \delta_{Trans}^l(T_S) - W_{Loss} \times \delta_{Loss}(T_S)$$

avec :

$$\delta_{Rec}^k(T_k) = \begin{cases} 1, & \text{if electrical/mechanical power is received} \\ 1 - \frac{T_0}{T_k}, & \text{if thermal power is received from a reservoir at } T_k \end{cases} \quad (11)$$

$$\delta_{Trans}(T_S) = \begin{cases} 1, & \text{if electrical/mechanical power is transferred} \\ 1 - \frac{T_0}{T_S}, & \text{if thermal power is transferred at } T_S \end{cases}$$

$$\delta_{Loss}(T_S) = \begin{cases} 1, & \text{if electrical/mechanical power is lost} \\ 1 - \frac{T_0}{T_S}, & \text{if thermal power is lost at } T_S \end{cases}$$

Equation (11) quantifies only the overall internal irreversibilities. In the global balance, it is necessary to take into account simultaneously the internal irreversibilities and losses to atmosphere. These losses are included in equation (12):

$$Ex_{Destruct}^i = T_0 \dot{S}_{gen}^{Total} + W_{Loss} \times \delta_{Loss}(T_S) \quad (12)$$

This formulation is simple in practice because it integrates all exergy destruction and losses of a component (both internal and external). Yet, it is always necessary to quantify output temperature and to know the input exergetic power: this problem is solved on paragraph 3.4.

4.1.2. Exergetic losses with mass flow and atmosphere

The components with inlet and outlet flows coming from the atmosphere are identified in an incomplete way by the Equation (11). Inlet and outlet exergy of these flows must be defined in addition to losses relative to components.

For losses induced by components, it is thus necessary to add the following term (Equation 13) to calculate the final criterion, which implicitly considers that energy that is rejected outside is not used to produce energy.

$$Ex_{Loss}^{flow} = \sum_{i=1}^{NO} m_i \times (h_i - T_0 \times s_i) - \sum_{j=1}^{NI} m_j \times (h_j - T_0 \times s_j) \quad (13)$$

4.1.3. Evaluation of exergetic destruction and losses within CYCLOP

The total exergetic destruction and loss on a system, whatever its structure, is the sum of the exergetic destruction and losses (to the atmosphere) for each component to which exergy

rejected to atmosphere via mass flows (Equations 12 and 13) is added. The total evaluation of destruction-losses should be minimized to maximize the energy production of the system (see Equation 14):

$$\dot{E}x_{Destruct} = \sum_i^{NCOMP} \dot{E}x_{Destruct}^i + \sum_{i=1}^{NO} m_i \times (h_i - T_0 \times s_i) - \sum_{j=1}^{NI} m_j \times (h_j - T_0 \times s_j) \quad (14)$$

Under CYCLOP formalism, “transfer” objects represent an energy flow between two components. The transfer efficiency “r” represents the percentage of energy transmitted between two components.

From a general point of view, the losses of exergy on an object “Transfer” are equal to:

$$\begin{aligned} Ex_{Destruct} &= (1 - r) \times \left[\sum_i W_i^{meca} + \sum_j W_j^{elec} + \sum_l W_l^{th} \times \left(1 - \frac{T_0}{T_l} \right) \right]_{in} \\ Ex_{Destruct} &= \left[\sum_i W_i^{meca} + \sum_j W_j^{elec} + \sum_l W_l^{th} \times \left(1 - \frac{T_0}{T_l} \right) \right]_{in} \\ &\quad - \left[\sum_i W_i^{meca} + \sum_j W_j^{elec} + \sum_l W_l^{th} \times \left(1 - \frac{T_0}{T_l} \right) \right]_{out} \end{aligned} \quad (15)$$

In this form, Equation (15) is a particular case of the general Equation (11) and thus does not require any modification of formulation. In the particular case of heat transfer, it can be considered that a source of heat supplies several exchangers.

Equation (12) requires to specify the temperature associated with the received thermal power. Physically, the exchanger must be represented by an energy source, from the point of view of the fluid.

The temperature T_k (Equation 11) of the “received” power is the mean value between T_{in} and T_{out} . It is yet possible with CYCLOP that a “heat exchanger” component is not connected to another, via an object “Transfer”. In this case, it directly supplies power, which is identified as a loss of exergy from system viewpoint.

The consideration of the thermal losses on the components must be studied because they induce a reduction in the capacity of work and transfer of the fluids used in the cycles of energy transformation: the same remark is valid for irreversibilities during chemical reactions.

The CYCLOP components that are directly concerned refer to those implied in an intrinsic heat transfer, that may be desired or not (case of heat loss).

These losses can be modelled as an output:

- for CYCLOP components
- for heat transfer between components (“transfer” object of CYCLOP)

Physically, the waste heat is considered in term of potential recoverable work for mass flows. This fact implies that only components CYCLOP that are crossed by mass have “the right to lose heat”. This fact also implies that a priori the thermal losses will be associated with the level of temperature of the fluid undergoing them.

Let us illustrate the enthalpic and entropic balances on an example of thermal losses for a heat exchanger.

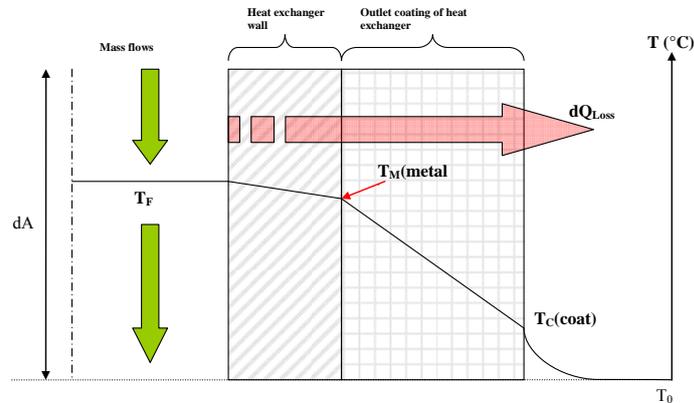


Figure 3 - Losses of energy through a metal and insulating wall of an exchanger

For an elementary element of surface dA (figure 3) of a heat exchanger, a fluid undergoes a heat loss called ∂Q_{Loss} , while crossing first the metal wall, then the insulating layer.

The principal assumptions involve:

- a constant radial temperature of the fluid for a turbulent flow. The temperatures with the interface between the fluid and the metal wall are thus identical,
- the materials of the metal wall and the insulating wall are homogeneous.

Entropy being a function of state, the change of the temperatures in the walls does not have any effect on the assessment of entropic flows.

The entropic balance on the metal wall is thus:

$$-\frac{\partial Q_{Loss}}{T_F} + \frac{\partial Q_{Loss}}{T_M} - \mathcal{S}_{gen}^{Metal} = 0 \quad (16)$$

The entropic balance on insulating wall takes the following expression:

$$-\frac{\partial Q_{Loss}}{T_M} + \frac{\partial Q_{Loss}}{T_C} - \mathcal{S}_{gen}^{coat} = 0 \quad (17)$$

The enthalpic balance is simple because the ∂Q_{Loss} quantity is preserved through the walls.

The exergetic balance between the transmitting fluid and the atmosphere gives the following relation:

$$\left[\begin{array}{l}
-\partial Q_{Loss} + \partial Q_{Loss} - T_0 \times \left(-\frac{\partial Q_{Loss}}{T_F} + \frac{\partial Q_{Loss}}{T_M} - \mathcal{E}_{gen}^{Metal} \right) \\
\text{Exergy balance on heat exchanger wall} \\
-\partial Q_{Loss} + \partial Q_{Loss} - T_0 \times \left(-\frac{\partial Q_{Loss}}{T_F} + \frac{\partial Q_{Loss}}{T_C} - \mathcal{E}_{gen}^{Coat} \right) \\
\text{Exergy balance on coating}
\end{array} \right] = 0 \quad (18)$$

$$\Leftrightarrow \underbrace{\partial Q_{Loss} \times \left(1 - \frac{T_0}{T_F} \right)}_{\text{Exergy lost by flows}} = \underbrace{\partial Q_{Loss} \times \left(1 - \frac{T_0}{T_C} \right)}_{\text{Exergy lost by heat exchanger}} + T_0 \times (\mathcal{E}_{gen}^{Coat} + \mathcal{E}_{gen}^{Metal})$$

Equation 18 shows that the thermal losses imply a loss of exergy which can be expressed according to the temperature of only the “transmitting” fluid.

Without any other information than the lost power (calculated from component output by CYCLOP), exergy lost by the system is equal to exergy lost by the fluid, which implies that the flow of lost exergy is a function of the temperature of the transmitting fluid.

For heat exchangers case, heat losses are modelled, with an exergy destruction during heat transfer between hot side and cold side, using Equation 15 and fixing the transfer efficiency value “r”.

4.2. Heat supplying system modelling

4.2.1. General formulation and hypothesis

By assuming that no chemical reaction on the systems occurs, the problem of heat transfer is always the same: a hot system transfers heat towards a cold system (both being crossed by undergoing mass flows with temperature variations and pressure) through a material wall.

Heat transfer, due to variations in temperature within the walls, makes it necessary to associate mean temperatures with the systems.

For an exchange between two mass flows, the formulated assumptions are the following ones (see Figure 4):

- There is no chemical reaction on hot or cold side
- On a cross section of the fluid (cold and hot side), temperatures and pressures are homogeneous (no radial gradients during heat transfer).

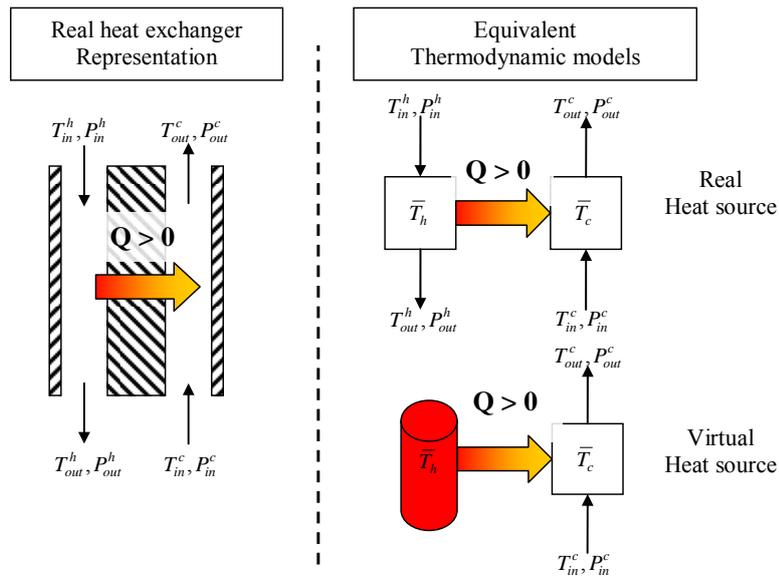


Figure 4 – Heat exchanger modelling with exergy theory

Thus, the hot side of the exchanger can be modelled as a sink of temperature emitting the required power Q , at a temperature T_h ; the calculation of this temperature takes into account the temperature change during the exchange.

This temperature is commonly called “entropic temperature” and makes it possible to reduce the hot side of an exchanger in a heat source to T_h constant.

4.2.2. Entropic temperature in ideal case: the Lorentz cycle

The Lorentz cycle (Lior, 2007) (reversible) (figure 5) considers that the exchanges with both heat and cold sources are not isothermal, which is not the case with Carnot cycle. It consists of a compression of an isentropic ideal gas ($1 \rightarrow 2$), followed by a heating phase ($2 \rightarrow 3$) where temperature increases gradually until the maximum temperature of the cycle, T_3 , is reached. The ideal gas undergoes an isentropic relaxation the ($3 \rightarrow 4$), then a cooling ($4 \rightarrow 1$) with a gradual reduction in temperature. It is also considered that there are no pressure losses during both warming and cooling.

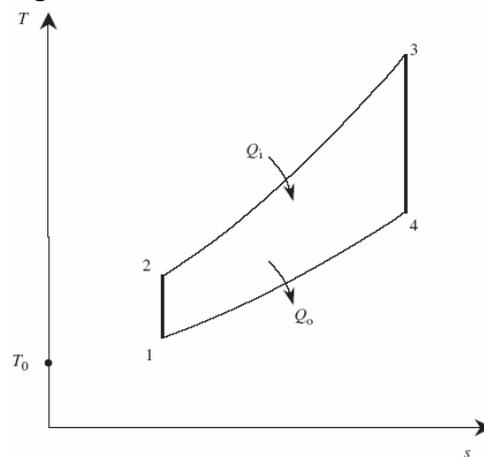


Figure 5 – (T,S) Diagram for Lorentz thermodynamic cycle

The exergetic balance relative to the so-called “half” hot exchanging gives:

$$\dot{S}_{gen}^h \times T_0 = \dot{E}x_{in}^h - \dot{E}x_{out}^h - Q \times \left(1 - \frac{T_0}{T_h}\right) = 0 \quad (19)$$

Consequently, the value of the entropic temperature of the hot source is:

$$\bar{T}_h = \frac{h(T_{in}^h) - h(T_{out}^h)}{s(T_{in}^h) - s(T_{out}^h)} = \frac{\int_{T_{out}^h}^{T_{in}^h} Cp.dT}{\int_{T_{out}^h}^{T_{in}^h} \frac{Cp}{T}.dT} \quad (20)$$

This result, obtained by an exergetic balance, is the classical expression for the entropic temperature (Lior, 2007). This equation is admitted for a constant pressure.

For a perfect gas and by considering C_p as a constant on the interval of temperature:

$$\bar{T}_h = \frac{(T_{in}^h - T_{out}^h)}{\ln(T_{in}^h / T_{out}^h)} \quad (21)$$

In the case of the real exchangers, all the irreversible phenomena must be taken into account.

4.2.3. General expression of entropic temperature

The cycle of Lorentz does not take into account the pressure losses due to the heat-transferring surfaces: consequently, there is generation of irreversibility. The exergetic balance on the so-called “half” hot exchanger is always identical, but the generated entropy \dot{S}_{gen}^h is not null any more.

$$\dot{S}_{gen}^h \times T_0 = \dot{E}x_{in}^h(T_{in}^h, P_{in}^h) - \dot{E}x_{in}^h(T_{out}^h, P_{out}^h) - Q \times \left(1 - \frac{T_0}{T_h}\right) \neq 0 \quad (22)$$

The term of exergetic power must be expressed according to the temperature change during transfer, according to the following equation:

$$Q \times \left(1 - \frac{T_0}{T_h}\right) = \int_{inlet}^{outlet} \left(1 - \frac{T_0}{T}\right) dQ \quad (23)$$

The entropic temperature \bar{T}_h is given by:

$$\bar{T}_h = \frac{\int_{T_{in}^h, P_{in}^h}^{T_{out}^h, P_{out}^h} Cp.dT + \left[v - T \left(\frac{\partial v}{\partial T} \right)_p \right] dp}{\int_{T_{in}^h, P_{in}^h}^{T_{out}^h, P_{out}^h} \frac{Cp.dT}{T} - \left(\frac{\partial v}{\partial T} \right)_p .dp} \quad (24)$$

The obtained entropic temperature, under the assumptions of perfect gas and constant C_p , is formally identical whereas their general expressions are different (Equations 20 and 21). By

considering the pressure losses, the level of temperature of exit T_{out}^h increases a little, which implies a reduction in the value of the entropic temperature \bar{T}_h .

4.3. Exergetic efficiency

The exergetic balance highlights the concept of thermodynamical loss. It is thus possible to define an exergetic efficiency as follows:

$$\eta_{ex} = \frac{\sum Ex_{Product}}{\sum Ex_{Sent}} \quad (25)$$

The exergetic power can represent a work, a mass or heat flow. According to the exergetic balance, it can be seen that the difference between the denominator and numerator of the exergetic efficiency η_{EX} (Bejan, 1984) (Equation 25) is rigorously equal to the system exergetic losses.

5. Application of exergy theory to a combined He/He-N₂/H₂O cycle

The combined cycle is a more complex case for application of exergy theory. This example implements a cycle of Brayton (as in the preceding case) as well as a cycle of Rankine with phase shift: steam generation is a source of exergetic losses, as it will be noted thereafter. This generating cycle is modelled with CYCLOP and optimized with a monoobjective genetic algorithm (Deb, 2002) implemented under the MULTIGEN environment (Gomez et al, 2008). The principle of the optimization procedure will not be recalled here.

5.1. Cycle description and identification of the exergetic losses

The combined cycle (figure 6) is composed of three loops implying three different coolants:

- The primary loop, using helium, with a cooling by of the Intermediate Heat Exchanger (IHX) and a compensation of the pressure losses per insertion of a blower before return on the engine
- The secondary loop, using a He-N₂ mixture (respectively 64% and 36% in mass), is a simple Brayton cycle: the IHX is the hot source whereas the steam generator is the cold well. This loop generates electricity.
- The tertiary loop, using water with high pressure, is a cycle of Rankine with a relaxation with high pressure and another with low pressure.

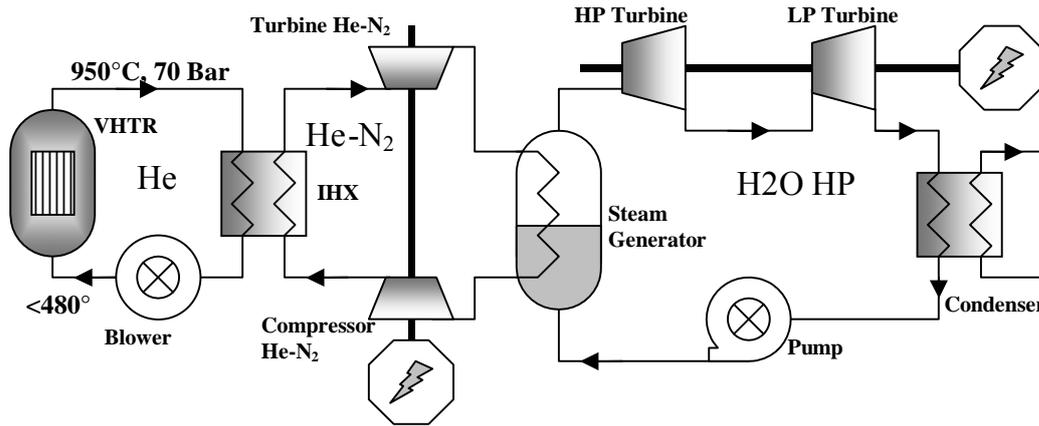


Figure 6 - Flowsheet of the pressured combined cycle He / He-N₂ / H₂O

The thermal losses of the steam generator are treated by assimilation with the lost power with a temperature equal to the logarithmic mean temperature value of the hot side flow. These assumptions imply an artificial maximization of the exergetic losses on the level of the steam generator.

Losses on the level of the condenser also appear because no cold source was associated in this cycle model performed with CYCLOP. The temperature of condensation being fixed at 32°C, the association of this temperature to the lost power will have no impact on the optimization of the cycle: the only adjustment variable will be the lost power with the condenser. Consequently, the expression of the exergetic losses of the Steam Generator influences the optimization process.

The variables of optimization selected for this cycle are the following ones:

- The outlet temperature of the gas turbine (He-N₂ loop)
- The outlet temperature of gas (secondary side He-N₂) of the Steam generator
- The pressure ratio of the high pressure steam turbine

The associated constraints are:

- The steam mass fraction at turbine exit must be higher than 85%, to avoid a damage of the turbine by a condensed water
- The mean logarithmic pinching temperature curve of the exchanger of intermediate heat (IHX) is higher or equal to 30°C
- The minimum pinch temperature of the steam generator is 10°C

The following stage consists in locating the exergetic losses on the system (see figure 6).

The cycle analysis leads to identify:

- Flows and energy production: 600 MWth resulting from the nuclear reactor, electrical production on the generating engine of the secondary loop (He-N₂) and the high pressure steam loop.
- Non used flows: latent heat at the condenser level.

Concerning condenser modelling, it must be pointed out that only the hot “half” exchanger (side condensation) is represented. The latent heat transmitted “to vacuum” is considered as lost by CYCLOP. Exergy destruction and losses are automatically calculated by CYCLOP

simulator component by component, using equation 12, and final criteria is calculated with equation 14.

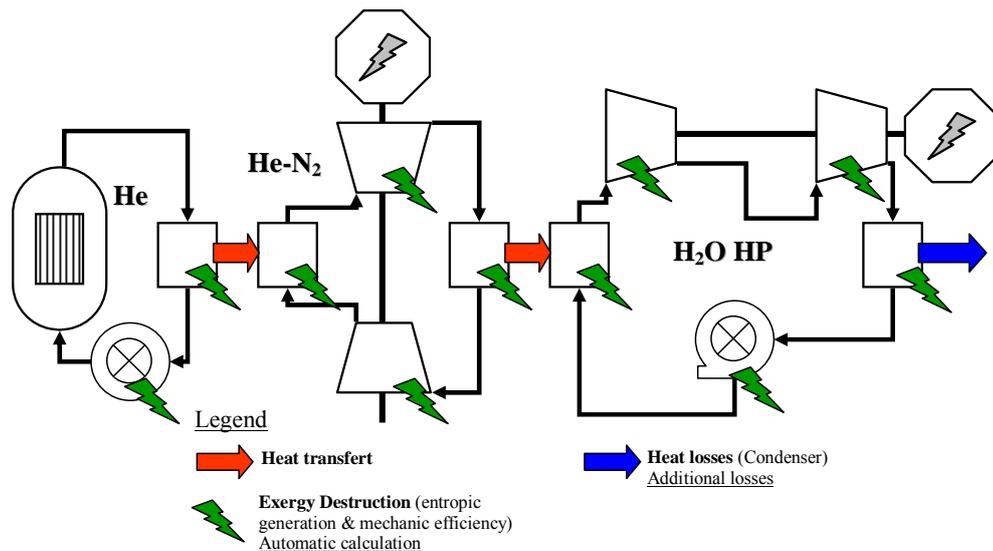


Figure 6 - Identification of the exergetic losses on the cycle

5.2. Optimization results

The optimization performed leads to a production of 288.8 MW for a total loss of exergy of 124,4 MW, which corresponds to an exergetic efficiency of 69.9%. Figure 7 displays the decomposition of the exergetic losses of the cycle components. Table 1 presents in detail the optimal operating conditions of the components. These values correspond to feasible orders of magnitude.

The corresponding optimization variables take the following values:

- Temperature of exit of the gas turbine (He-N₂): 590.9°C
- Temperature of exit gas (secondary side He-N₂) of the Steam generator: 164.8°C
- Pressure ratio of relaxation of the high pressure steam turbine: 36.7.

The steam generator, with a loss of 38 MW exergy, contributes to 30.5% of the total losses of the cycle.

This value is due to the combined effect of the following phenomena:

- A temperature pinching of 30°C
- Pressure losses of 20 bar (vaporization site) and 0.4 bar (gas side He-N₂)
- Thermal losses of 1.0 MW (exergetic)

The parameters of the genetic algorithm used in MULTIGEN environment (Gomez et al., 2008) are:

- Number of individuals: 100
- Number of generations: 200
- Crossover probability: 90%
- Mutation probability: 50%

Table 1 – Optimal characteristics of components for minimum exergy destruction

Component	Power (MW)	Efficiency ¹ (%) / Pinch temperature (°C)	Pressure discharge (bar) / pressure ratio	Maximal Temperature (°C)	Maximale Pressure (Bar)
IHX (He loop)	604	94.6% / 30°C	0.4 bar (hot) / 0.4 bar (cold)	950	70
Blower (He loop)	7.6	88%	x 1.02	434	71
Turbine (He-N ₂ loop)	381.3	93%	x 2.89	920	64.6
Compressor (He-N ₂ loop)	252.4	88%	x 2.96	392	65
Steam generator	474	30°C	0.4 bar (hot) / 20 bar (cold)	590	150
HP Turbine (steam loop)	108.7	86.5%	x 37.00	561	130
LP Turbine (steam loop)	71	86.5%	x 73.77	139	3,5
Condenser (steam loop)	296	- / -	0 bar (hot)	32	0.05
Pump (steam loop)	2.44	88%	x 3149.97	32.85	150
Electric Generators	298.6	98.7%			
Network Transmission (nuclear plant output power)	288.8	98%			
He loop flow (kg/s)	222.94				
He-N ₂ loop flow (kg/s)	580.81				
H ₂ O HP loop flow (kg/s)	141.44				

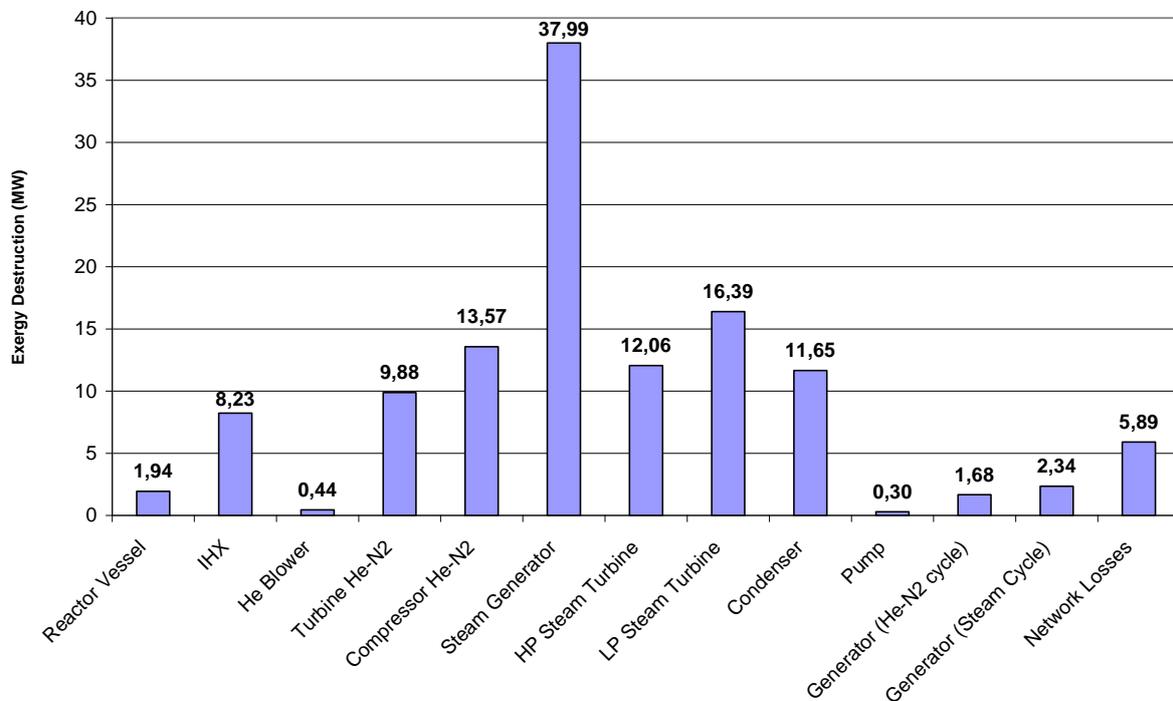


Figure 7 – Exergy destruction analysis for combined cycle He / He-N₂ / H₂O

¹ Isentropic efficiency for compressor and turbines, efficiency (temperatures) for heat exchangers

This study illustrates that the performances of the steam generator must be improved to increase electrical production. The generator engine of the secondary loop He-N₂ (respectively the steam turbine) accounts for 18.8% of the losses (respectively 22.9 %) for a total of 51.9 MW (exergy) for the mechanical energy production. Let us recall that these losses reached 40,7 MW (exergy) for the direct cycle GT-MHR.

The exergy destruction with the condenser is weaker, with 11.6 MW, but the half-exchanger side cold utility was not taken into account.

Due to the three loops, the impact analysis of the improvement of the equipment performances is complex, but a decrease in exergy destruction in the steam generator will lead to increase production. The steam cycle being limited in design, by the maximum pressure (150 bar) and by the temperature of the condenser, further work will now be devoted to the secondary loop and to the decrease in pinch temperature.

Conclusion

The application of the exergetic balance presents the advantage to compare, on the same basis, various forms of energy (thermal, electrical and mechanical) by a simultaneous consideration of first and second principles of thermodynamics. The major concept of the exergy theory is the concept of “useful energy” of an energy source. Mechanical, thermal or chemical non-equilibrium is at the origin of this exergetic potential.

The irreversibility created during transformations, or energy transfers, are taking into account by an entropic balance. Since such dissipated energy cannot be recovered, it is thus advisable to minimize them. By extension, the losses of recoverable energy (mainly due to thermal effects) will have to be also minimized and are considered as the irreversibility, since they are lost for energy transformation.

The minimization of exergy destruction requires an increase in equipment efficiency either at the level of their operating conditions (flows, pressures and temperatures), or at technological level (intrinsic entropic losses of equipment, pressure losses in particular). This implies an increase in cost, independently of the operating conditions.

The approach, proposed in this article, consists in minimizing the internal and external losses of a system for generating cycles and cogeneration systems. Exergy assessment will now be used and extended to the cogeneration of hydrogen and electricity which constitutes a natural perspective for VHTR reactors.

Nomenclature

C_p	= specific heat (J/kg/K)
dA	= elementary area (m ²)
δQ_{Loss}	= elementary heat loss (W)
D	= exergy flow rate produced by the system (W)
e_k	= specific flow exergy (J/kg)
$Ex_{Destruct}^i$	= flow exergy rate (W)
m	= mass flow (kg/s)
h	= specific enthalpy (J/kg)
P	= pressure (bar)

Q	= heat Power (W)
r	= energy transfer efficiency (%)
s	= specific entropy (J/kg/K)
\dot{S}_{gen}	= entropy generation rate (W/k)
T	= temperature (K)
W	= power (W)

Greek Symbols

v	= molar volume of gaz (m ³ /mol)
η_{ex}	= exergy efficiency (%)

Subscripts

c	= cold
C	= coat
elec	= electricity
h	= hot
Int	= internal
mech	= mechanical
M	= metal
NI	= Number of inlet flows
NO	= Number of outlet flows
NHS	= Number of Heat Sources
0	= atmospheric conditions (25 °C, 1 atm)
Product	= product
Rec	= Received
Trans	= transferred
Loss	= losses
S	= considered system
Sent	= sent
th	= thermal

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