Advanced Exergy Analysis for Chemically Reacting Systems – Application to a Simple Open Gas-Turbine System*

Tatiana Morosuk [1]**, George Tsatsaronis [2]
[1] Institute of Marine Propulsion Plants Operation, Maritime Academy of Szczecin, Poland
[2] Institute for Energy Engineering, Technische Universität Berlin, Germany
E-mail: [1]morozyuk@iet.tu-berlin.de; [2] tsatsaronis@iet.tu-berlin.de

Abstract

A conventional exergy analysis has some limitations, which are significantly reduced by an advanced exergy analysis. The latter evaluates: (a) the interactions among components of the overall system (splitting the exergy destruction into endogenous and exogenous parts); and, (b) the real potential for improving a system component (splitting the exergy destruction into unavoidable and avoidable parts). The main role of an advanced exergy analysis is to provide engineers with additional information useful for improving the design and operation of energy conversion systems. This information cannot be supplied by any other approach. In previous publications, approaches were presented that were appropriate for application to closed thermodynamic cycles, without chemical reactions (e.g., refrigeration cycles). Here a general approach is discussed that could be applied to systems with chemical reactions. Application of this approach to a simple gas-turbine system reveals the potential for improvement and the interactions among the system components.

Keywords: *Exergy analysis, exergy destruction, avoidable exergy destruction, endogenous exergy destruction, gas-turbine system.*

1. Introduction

A conventional exergy analysis identifies the magnitude and the location of the real thermodynamic inefficiencies (Bejan et al., 1996). However, in revealing the causes of these inefficiencies a conventional analysis fails to identify the contributions by the other components to the exergy destruction within the component being considered. Knowledge of the interactions among components and of the potential for improving each important component is very useful in improving the overall system (Tsatsaronis, 1999a).

Splitting the exergy destruction within each component of an energy conversion system into endogenous/exogenous parts ($\dot{E}_{D,k} = \dot{E}^{EN}_{D,k} + \dot{E}^{EX}_{D,k}$) and unavoidable/ avoidable parts ($\dot{E}_{D,k} = \dot{E}^{UN}_{D,k} + \dot{E}^{AV}_{D,k}$), and combining the two approaches of splitting the exergy destruction ($\dot{E}_{D,k} = \dot{E}^{UN,EN}_{D,k} + \dot{E}^{UN,EX}_{D,k} + \dot{E}^{AV,EN}_{D,k} + \dot{E}^{AV,EX}_{D,k}$) enhances an exergy analysis and improves the quality of the conclusions obtained from it (Tsatsaronis and Park, 2002; Cziesla et al., 2006; Morosuk and Tsatsaronis, 2006a, 2006b, 2008; Tsatsaronis et al., 2006; Kelly, 2008; Tsatsaronis and Morosuk, 2007). These parts of exergy destruction are defined as follows.

The *endogenous* part of exergy destruction ($\dot{E}^{EN}_{D,k}$) is associated only with the irreversibilities occurring in the k^{th} component when all other components operate in an ideal way and the component being considered operates with its current efficiency.

The *exogenous* part of exergy destruction ($\dot{E}^{EX}_{D,k}$) is caused within the k^{th} component by the irreversibilities that occur in the remaining components.

To better understand the interactions among components, the exogenous exergy destruction within the k^{th} component should also be split.

Splitting the exogenous exergy destruction within the k^{th} component ($\dot{E}^{EX,r}_{D,k}$) reveals the effect that the irreversibility within the r^{th} component has on the exergy destruction within the k^{th} component. The sum of all $\dot{E}^{EX,r}_{D,k}$ terms is lower than the exogenous exergy destruction within the k^{th} component. The difference is caused by the simultaneous interactions of all (n–1) components. This difference, the *mexogenous exergy destruction* ($\dot{E}^{mexo}_{D,k}$) is calculated from (Tsatsaronis and Morosuk, 2007)

$$\dot{E}^{mexo}_{D,k} = \dot{E}^{EX}_{D,k} - \sum_{\substack{r=1 \\ r\neq k}}^{n-1} \dot{E}^{EX,r}_{D,k} \tag{1}$$

where n denotes the total number of system components and r refers to all but the k^{th} system component.

Unavoidable ($\dot{E}^{UN}_{D,k}$) is the part of exergy destruction within one system component that cannot be eliminated even if the best available technology in the near future would be applied.

The *avoidable* ($\dot{E}^{AV}_{D,k}$) exergy destruction is the difference between total and unavoidable exergy destruction and represents the real potential for improving the system component.

By combining the two approaches for splitting exergy destruction we obtain

*This paper is an updated version of a paper published in the ECOS08 proceedings. It is printed here with permission of the authors and organizers.
**Corresponding Author

- the *unavoidable endogenous* ($\dot{E}_{D,k}^{UN,EN}$) and the *unavoidable exogenous* ($\dot{E}_{D,k}^{UN,EX}$) parts of exergy destruction, and
- the *avoidable endogenous* ($\dot{E}_{D,k}^{AV,EN}$) and the *avoidable exogenous* ($\dot{E}_{D,k}^{AV,EX}$) parts of exergy destruction that can be reduced by improving the component being considered, or the remaining subsystem (single components or subsystem structure), respectively.

The splitting of the exogenous part of the exergy destruction (Eq.(1)) should also be applied to the splitting of the unavoidable exogenous, and, more importantly, the avoidable exogenous parts of exergy destruction.

Figure 1 summarizes all options for splitting the exergy destruction within the k^{th} component (Tsatsaronis and Morosuk, 2007).

2. The approach for splitting exergy destruction

Past publications considered the splitting of exergy destruction into unavoidable and avoidable parts (Tsatsaronis, 1999a, 1999b; Tsatsaronis and Park, 2002; Cziesla et al., 2006) as well as into endogenous and exogenous parts (Morosuk and Tsatsaronis, 2006a, 2006b, 2008; Tsatsaronis et al., 2006; Kelly, 2008; Tsatsaronis and Morosuk, 2007; Kelly et al., 2009). The calculation of endogenous exergy destruction in a component when a chemical reaction takes place in the remaining components represents a problem because no ideal ("theoretical") conditions can be defined for the reaction process. The so-called "engineering approach" was developed to overcome this problem (Tsatsaronis et al., 2006; Kelly, 2008; Kelly at al., 2009). Here a new general approach is presented that can be applied easier than the engineering approach to complex energy conversion systems. The approach described in the following has some slight differences compared with the approach used for refrigeration systems (Morosuk and Tsatsaronis, 2006a, 2006b, 2008; Tsatsaronis et al., 2006; Tsatsaronis and Morosuk, 2007). The approach presented here overcomes the most important limitations of a conventional exergy analysis (Tsatsaronis, 1999a). The present approach could have some limitations associated with the size and complexity of the overall system under investigation.

2.1. Real operating conditions

First a detailed exergy analysis is conducted for the system being considered operating at real conditions. The exergy destruction in each system component is calculated separately. For the simple gas-turbine system shown in Figure 2, the real operating conditions are given on a *T-s* diagram in Figure 3. The real process consists of states 1, 2R, 3R, 4R and 5R (Figure 3 and Table 1).

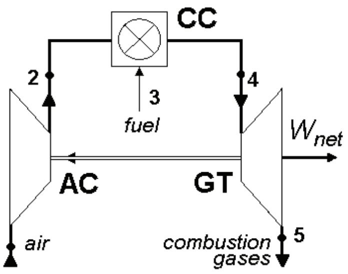

Figure 2: Schematic of a simple gas-turbine power system.

The results from the conventional exergy analysis of this system are summarized in the first four columns of Table 2 with

$$\dot{E}_{D,AC} = \dot{E}_{F,AC} - \dot{E}_{P,AC} = \dot{W}_{AC} - \left(\dot{E}_2 - \dot{E}_1\right),$$

$$\dot{E}_{D,CC} = \dot{E}_{F,CC} - \dot{E}_{P,CC} = \dot{E}_3 - \left(\dot{E}_4 - \dot{E}_2\right),$$

and

$$\dot{E}_{D,GT} = \dot{E}_{F,GT} - \dot{E}_{P,GT} = \left(\dot{E}_4 - \dot{E}_5\right) - \dot{W}_{GT}.$$

This analysis, however, does not provide any information with respect to the potential for improving the overall system and the single components, neither with respect to the interactions among the components.

For illustration purposes, we have assumed that the overall gas-turbine system generates net power $\dot{W}_{net}$ = 100 MW, the isentropic efficiencies of the air compressor and the expander are $\eta_{AC} = 0.88$ and $\eta_{GT} = 0.91$, respectively, the pressure ratio in the expander amounts to $p_4 / p_1 = 15$, the temperature at the inlet to the expander is 1500 K, and the relative pressure drop in the combustion chamber is 0.09. The resulting mass flow rates are $\dot{m}_{air}^{R}$ = 247.8 kg/s, $\dot{m}_{fuel}^{R}$ = 5.489 kg/s and $\dot{m}_{cg}^{R}$ = 253.2 kg/s. In the advanced exergy analysis discussed in the following, we keep constant the ratio of the mass flow rates, $\frac{\dot{m}_{air}^{R}}{\dot{m}_{fuel}^{R}}$ = 45.14 = *const*, and the net power generated by the overall system, $\dot{E}_{P,tot} = \dot{W}_{net}$ = 100 MW = *const*.

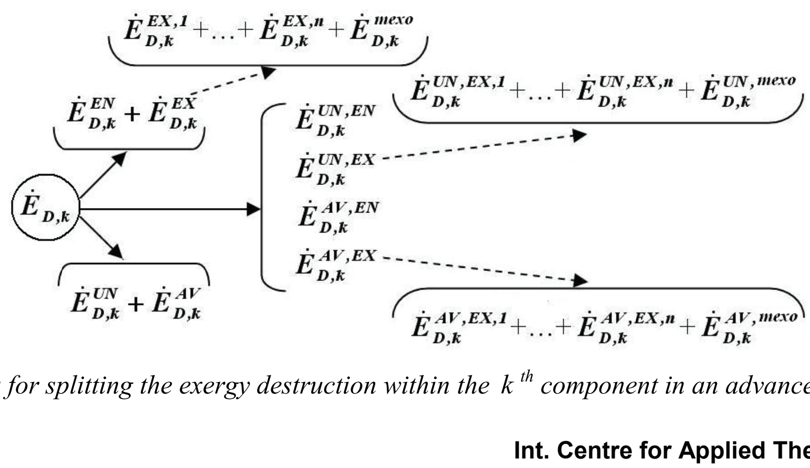

Figure 1: Options for splitting the exergy destruction within the k^{th} component in an advanced exergy analysis.

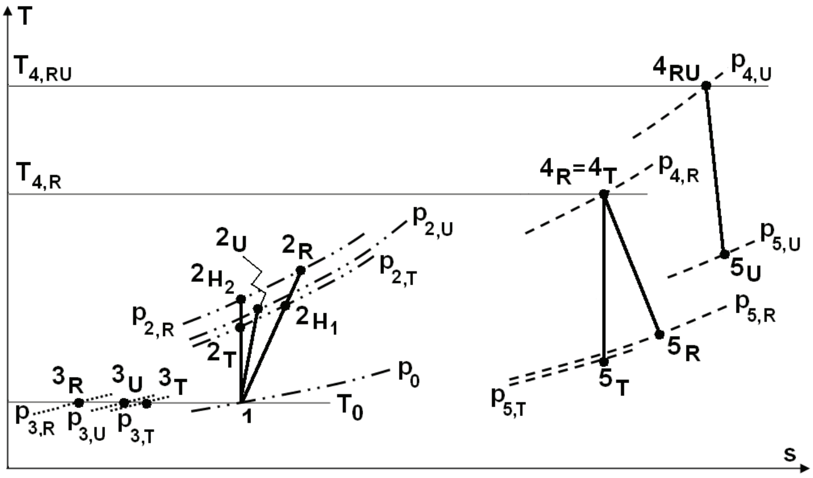

Figure 3: Real, theoretical, unavoidable and hybrid processes for simple gas-turbine power system showed in Figure 2: — · · — · · — air, ·················· fuel, – – – – – – combustion gases.

Table 1. Thermodynamic data for the real (R), theoretical (T), unavoidable (U) and hybrid processes (H) of the simple gas-turbine power system.

Stream	T [K]	p [bar]	e^{PH} [MJ/kg]	e^{CH} [MJ/kg]	e [MJ/kg]
1	298	1.013	0	0	0
2T	636	15.2	0.350	0	0.350
$2H_2$	652	16.71	0.368	0	0.368
2U	662	15.35	0.366	0	0.366
$2H_1$	680	15.2	0.376	0	0.376
2R	698	16.71	0.396	0	0.396
3T	298	15.2	0.418	51.38	51.8
3U	298	15.5	0.421	51.38	51.8
3R	298	18	0.445	51.38	51.83
4U	2100	15.2	1.878	0.020	1.898
4R= 4T	1500	15.2	1.113	0.005	1.119
5U	943	1.025	0.629	0.020	0.649
5R	859	1.025	0.281	0.005	0.286
5T	1216	1.013	0.228	0.005	0.233

For calculating the values of unavoidable irreversibilities within each system component, we assumed conditions that cannot be realized in the next decade: $\eta_{AC}^{UN} = 0.93$, $\eta_{GT}^{UN} = 0.96$, an adiabatic combustion process with T_4=2100 K and a relative pressure drop in the combustion chamber of 0.01.

The composition of the combustion gases for the process with only unavoidable irreversibilities is different than the composition of combustion gases for the real process. Therefore, for showing the process with unavoidable irreversibilities we need four more isobaric lines $p_{2,U}$, $p_{3,U}$, $p_{4,U}$ and $p_{5,U}$ (Figure 3).

For calculating the value of the unavoidable exergy destruction within the kth component, the following procedure is used (detailed description is given in Tsatsaronis and Park, 2002; Cziesla et al., 2006).

$$\dot{E}_{D,k}^{UN} = \dot{E}_{D,k}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \tag{2}$$

where the value $\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}$ should be calculated using the process with unavoidable irreversibilities.

The values $\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}$ are given in Table 2 and the values $\dot{E}_{D,k}^{UN}$ and $\dot{E}_{D,k}^{AV}$ are presented in Table 3. The exergetic efficiency of the overall gas-turbine power system operating at the given pressure ratio and at conditions that are associated with unavoidable exergy destruction is ε_{tot}^{UN} = 40.4%. Thus the potential for improving the overall efficiency of such a system (without an air preheater) and at the given pressure ratio of about 15 is approximately 5 percentage points.

2.2. Theoretical operating conditions

For splitting the exergy destruction into endogenous and exogenous parts, and for further splitting the exogenous part of the exergy destruction, we need to describe the theoretical operation conditions for each component of the gas-turbine power system.

The theoretical operational conditions for the air compressor and the gas turbine are similar: $\dot{E}_{D,AC}^{T} = 0$ ($\varepsilon_{AC}^{T} = 1$ or $\eta_{AC}^{T} = 1$) and $\dot{E}_{D,GT}^{T} = 0$ ($\varepsilon_{GT}^{T} = 1$ or $\eta_{GT}^{T} = 1$).

The following assumptions are made for the theoretical combustion chamber:

- The thermodynamic properties of the combustion gas and the composition of it remain the same as in the real operating conditions (state $4T$ = state $4R$),
- The pressure drop in the combustion chamber is zero, $p_2 = p_4$,
- State $4T(=4R)$ should be the result of the chemical reaction between the streams at states $2T$ and $3T$,
- The excess air at theoretical conditions is equal to the excess air in the real process: $\frac{\dot{m}_{air}^{T}}{\dot{m}_{fuel}^{T}} = \frac{\dot{m}_{air}^{R}}{\dot{m}_{fuel}^{R}}$, and

- With respect to mass balances, the gas-turbine power system is split into two sub-systems: sub-system I is the combination of the air compressor with the combustion chamber while sub-system II consists only of the turbine (Figure 4).

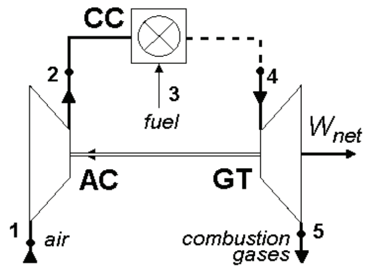

Figure 4: Sub-systems of a simple gas-turbine power system.

In general a new subsystem should be introduced after any chemical reactor in which the mass balance cannot be fulfilled.

The theoretical process is $1 - 2_T - 4_T$ (2_T+3_T) $- 5_T$ (Figure 3).

The condition $\dot{E}^T_{D,CC} = 0$ can be achieved through a combination of the following two equations (3) and (5).

- Since we cannot fulfill the mass, energy and exergy balances simultaneously for the theoretical combustion chamber, we fulfill only the exergy balance:

$$\dot{E}_{2T} + \dot{E}_{3T} = \dot{E}_{4T}\,, \tag{3}$$

or

$$e_{2T} \cdot \dot{m}^T_{air} + e_{3T} \cdot \dot{m}^T_{fuel} = e_{4T} \cdot \dot{m}^T_{cg}\,, \tag{4}$$

- In addition, we fulfill the following balance

$$\dot{W}_{net} = w^T_{GT} \cdot \dot{m}^T_{cg} - w^T_{AC} \cdot \dot{m}^T_{air} \tag{5}$$

with $\dot{W}_{net}$ = 100 MW.

For the gas-turbine system at theoretical operating conditions we have: $\dot{m}^T_{air}$ = 119.8 kg/s, $\dot{m}^T_{fuel}$ = 2.654 kg/s and $\dot{m}^T_{cg}$ = 160.3 kg/s.

It is apparent that $\dot{m}^T_{air} + \dot{m}^T_{fuel} \neq \dot{m}^T_{cg}$. As we mentioned before, the overall system is split into two sub-systems, and, therefore, we do not need to consider this mass balance.

If the overall system would contain additional components, we would use the following procedures:

A throttling valve should be replaced by an expander (EX) with η_{EX}=1 (Morosuk and Tsatsaronis, 2006a, 2008).

For a heat exchanger (including an absorber or generator, for example for an absorption refrigeration machine (Morosuk and Tsatsaronis, 2008)), only the condition $\dot{E}_{D,k} = min$ is possible, with ΔT_{pinch}=0.

We conclude that the overall energy conversion system cannot always be described at ideal operating conditions ($\dot{E}_{D,tot}$ = 0 and $\varepsilon_{D,tot}$ = 1). When this is not possible, theoretical operational conditions should be used (Morosuk and Tsatsaronis, 2006a, 2006b; Tsatsaronis et al., 2006; Kelly, 2008) with $\dot{E}^T_{D,k} = min$ and $\varepsilon^T_k = \max$.

2.3. Hybrid processes - 1

For splitting the exergy destruction into the endogenous/exogenous parts (or into the unavoidable endogenous/unavoidable exogenous parts) we use hybrid processes in which only one component is real, i.e. operates with its real efficiency (or its unavoidable efficiency) while all other components operate in an ideal/theoretical way. In this case, the exergy destruction within the component being considered represents the endogenous (the unavoidable endogenous) exergy destruction. Thus, step-by-step introducing irreversibilities successively in each system component enables us to calculate the endogenous (the unavoidable endogenous) exergy destruction within each component.

For calculating the endogenous part of the exergy destruction within system components, the following hybrid processes - 1 should be analyzed (Figure 3). In each such process only one component is assumed to be irreversible, while the remaining components operate at the theoretical operating conditions:

- Air compressor ($\dot{E}^{EN}_{D,AC}$) –
  process $1 - 2_{H1} - 4_T$ $(3_T + 2_{H1})$ $- 5_T$,
- Combustion chamber ($\dot{E}^{EN}_{D,CC}$) –
  process $1 - 2_{H2} - 4_T$ $(3_R + 2_{H2})$ $- 5_T$, and
- Gas turbine ($\dot{E}^{EN}_{D,GT}$) –
  process $1 - 2_T - 4_T$ $(3_T + 2_T)$ $- 5_R$.

The mass flow rates of air, fuel and combustion gases should be calculated for each hybrid process. For the hybrid process with irreversibilities either only in the air compressor or only in the gas turbine, the procedure described by Eqs. (3)-(5) is used. For the hybrid process with only irreversibilities in the combustion chamber, the exergy balance in this component becomes

$$\dot{E}_2 + \varepsilon_{CC}\dot{E}_3 = \dot{E}_4 \tag{6}$$

where ε_{CC} is the exergetic efficiency of the combustion chamber at real operating conditions.

The values $\dot{E}^{EN}_{D,k}$ as well as the values $\dot{E}^{EX}_{D,k}$ are given in Table 3. The values $\dot{E}^{EN}_{P,k}$ (Table 2) should also be calculated because they are needed for the next step of the advanced exergy analysis.

To calculate the unavoidable endogenous part of the exergy destruction within a system component, we apply the following equation

$$\dot{E}^{UN,EN}_{D,k} = E^{EN}_{P,k}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \tag{7}$$

The results obtained for $\dot{E}^{UN,EN}_{D,k}$, $\dot{E}^{UN,EX}_{D,k}$, $\dot{E}^{AV,EN}_{D,k}$ and $\dot{E}^{AV,EX}_{D,k}$ are given in Table 3.

2.4. Hybrid processes - 2

For splitting the exogenous part of the exergy destruction within each system component, the following hybrid processes – 2 should be introduced (Figure 3). In every one of these processes, two components are assumed to be irreversible:

- Air compressor and combustion chamber for calculating the values $\dot{E}_{D,AC}^{EX,CC}$ and $\dot{E}_{D,CC}^{EX,AC}$ – process $1 – 2_R – 4_R$ $(3_R + 2_R) – 5_T$,
- Air compressor and gas turbine for calculating the values $\dot{E}_{D,AC}^{EX,GT}$ and $\dot{E}_{D,GT}^{EX,AC}$ – process $1 – 2_{H1} – 4_T$ $(3_T+2_{H1}) – 5_R$, and
- Combustion chamber and gas turbine for calculating the values $\dot{E}_{D,CC}^{EX,GT}$ and $\dot{E}_{D,GT}^{EX,CC}$ – process $1 – 2_{H2} – 4_R$ $(3_R + 2_{H2}) – 5_R$.

The value of $\dot{E}_{D,k}^{EX,r}$ (Table 3) is calculated by

$$\dot{E}_{D,k}^{EX,r} = \dot{E}_{D,k}^{k,r} - \dot{E}_{D,k}^{EN} \tag{8}$$

The values $\dot{E}_{D,k}^{k,r}$ are given in Table 2.

For splitting the unavoidable exogenous part of the exergy destruction within a system component, we need a procedure similar to the one described by Eqs. (8) and (9)

$$\dot{E}_{D,k}^{UN,EX,r} = \dot{E}_{D,k}^{UN,k,r} - \dot{E}_{D,k}^{UN,EN} \tag{9}$$

with

$$\dot{E}_{D,k}^{UN,k,r} = \dot{E}_{P,k}^{k,r}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \tag{10}$$

The values of $\dot{E}_{P,k}^{k,r}$ are given in Table 2 and the results are presented in Table 3.

3. Discussion and conclusion

When we evaluate the thermodynamic performance of a system component, it is very helpful to know (a) what part of the exergy destruction is caused by which other component, and (b) what part of the exergy destruction within the component being considered could be avoided. This information is obtained with the aid of theoretical, hybrid and unavoidable processes that are considered together with the real process.

This paper demonstrates how to define all these processes and how to split the exergy destruction within a system component into its parts unavoidable/avoidable and endogenous/ exogenous as well as unavoidable endogenous, unavoidable exogenous, avoidable endogenous and avoidable exogenous. The system evaluation is based on the last two parts of exergy destruction.

Compared with the conventional exergy analysis of a simple gas-turbine power system we obtain the following additional information with the aid of an advanced exergy analysis:

1. The potential for improving the efficiency of the overall system is approximately 5 percentage points because over 70% of the exergy destruction in the overall system is unavoidable.
2. Only one fourth of the exergy destruction in the combustion chamber is avoidable. For the combustion chamber, the avoidable endogenous exergy destruction (to be reduced, for example, by increasing the temperature T_4) is four times higher than the avoidable exogenous exergy destruction (to be reduced through improvements in the air compressor and the expander).
3. Over 50% of the exergy destruction in the air compressor is exogenous whereas this percentage is approximately 27% for the expander and 22% for the combustion chamber.
4. An improvement in the expander would affect not only the endogenous avoidable exergy destruction of this component but also the exogenous avoidable exergy destruction within the combustion chamber.

Nomenclature

$\dot{E}$	exergy rate [W]
e	specific exergy [J/kg]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [bar]
$\dot{Q}$	heat rate [W]
s_{gen}	specific entropy generation [J/kg·K]
T	temperature [K]
$\dot{W}$	power [W]

Greek symbols

Δ	difference
ε	exergetic efficiency
η	isentropic efficiency

Abbreviations

AC	air compressor
CC	combustion chamber
GT	gas turbine (expander)

Subscripts

D	destruction
F	fuel
H	point of a hybrid process
k	k th component
P	product
R	point of a real process
U	point of a process with unavoidable exergy destruction
T	point of a theoretical process
tot	overall system
0	thermodynamic environment

Superscripts

AV	avoidable
ch	chemical exergy
EN	endogenous
EX	exogenous
k	k th component
mexo	mexogenous
n	number of components
ph	physical exergy
r	r th component (different from the k th component being considered)
R	real operation conditions
T	theoretical operation conditions
UN	unavoidable

Table 2: Data obtained from the conventional exergy analysis and some data for the advanced exergy analysis.

Component	Real operating conditions ($\dot{E}_{L,tot}=72.47$ MW)				Unavoidable operating conditions	Hybrid operating conditions - 1	Hybrid operating conditions - 2	
	$\dot{E}_{F,k}$ [MW]	$\dot{E}_{P,k}$ [MW]	$\dot{E}_{D,k}$ [MW]	ε_k [%]	$\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}$	$\dot{E}_{P,k}^{EN}$ [MW]	$\dot{E}_{D,k}^{k,r}$ [MW]	$\dot{E}_{P,k}^{k,r}$ [MW]
AC	103.54	98.08	5.46	94.7	0.033	46.58	$\dot{E}_{D,AC}^{AC,CC}=4.52$; $\dot{E}_{D,AC}^{AC,GT}=3.09$	$\dot{E}_{D,AC}^{UN,AC,CC}=81.23$; $\dot{E}_{D,AC}^{UN,AC,GT}=54.03$
CC	284.48	185.50	98.98	65.2	0.398	145.3	$\dot{E}_{D,CC}^{CC,AC}=81.98$; $\dot{E}_{D,CC}^{CC,GT}=92.11$	$\dot{E}_{D,CC}^{UN,CC,AC}=153.7$; $\dot{E}_{D,CC}^{UN,CC,GT}=172.7$
GT	210.78	203.50	7.28	96.5	0.0103	148.3	$\dot{E}_{D,GT}^{GT,AC}=5.62$; $\dot{E}_{D,GT}^{GT,CC}=6.61$	$\dot{E}_{D,GT}^{UN,GT,AC}=157.1$; $\dot{E}_{D,GT}^{UN,GT,CC}=184.8$
Overall system	284.48	100	111.72	35.2				

Table 3: Conventional and advanced exergy analyses for the simple gas-turbine power system.

Component	$\dot{E}_{D,k}$ [MW]	$\dot{E}_{D,k}^{EN}$ [MW]	$\dot{E}_{D,k}^{EX}$ [MW]			$\dot{E}_{D,k}^{UN}$ [MW]	$\dot{E}_{D,k}^{AV}$ [MW]	Splitting $\dot{E}_{D,k}^{real}$ [MW]							
								$\dot{E}_{D,k}^{UN}$				$\dot{E}_{D,k}^{AV}$			
								$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$			$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$		
AC	5.46	2.66	2.80	CC	1.86	3.24	2.22	1.54	1.70	CC	1.14	1.12	1.10	CC	0.72
				GT	0.43					GT	0.25			GT	0.18
				mexo	0.51					mexo	0.31			mexo	0.20
CC	98.98	77.52	21.46	AC	4.46	73.90	25.08	57.82	16.08	AC	3.34	19.70	5.38	AC	1.12
				GT	14.59					GT	10.91			GT	3.68
				mexo	2.41					mexo	1.83			mexo	0.58
GT	7.28	5.30	1.98	AC	0.32	2.10	5.18	1.53	0.57	AC	0.09	3.77	1.41	AC	0.23
				CC	1.31					CC	0.38			CC	0.93
				mexo	0.35					mexo	0.10			mexo	0.25
Overall system	111.72	85.48	26.24			79.24	32.48	60.89	18.35			24.59	7.89		

References

Bejan, A., Tsatsaronis, G. and Moran, M., 1996, *Thermal design and optimization*. New York: Wiley.

Cziesla, F., Tsatsaronis, G. and Gao, Z., 2006, "Avoidable thermodynamic inefficiencies and costs in an externally fired combined cycle power plant", *Energy Int. J.*, Vol. 31, No.10–11, pp. 1472–1489.

Kelly, S., 2008, "Energy systems improvement based on endogenous and exogenous exergy destruction", Ph.D. dissertation, Technische Universität Berlin, Germany.

Kelly, S, Tsatsaronis, G. and Morosuk, T., 2009, "Advanced exergetic analysis: Approaches for splitting the exergy destruction into endogenous and exogenous parts", *Energy Int. J.*, Vol. 34, pp. 384-391.

Morosuk, T. and Tsatsaronis, G., 2006a, "The "Cycle Method" used in the exergy analysis of refrigeration machines: from education to research", *Proceedings of the 19th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems*, Frangopoulos, C. et al., ed., Aghia Pelagia, Crete, Greece, Vol. 1, pp. 157–63.

Morosuk, T. and Tsatsaronis, G., 2006b, "Splitting the exergy destruction into endogenous and exogenous parts – application to refrigeration machines", *Proceedings of the 19th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems*, Frangopoulos, C. et al., ed., Aghia Pelagia, Crete, Greece, Vol. 1, pp. 165–172.

Morosuk, T. and Tsatsaronis, G., 2008, "New approach to the exergy analysis of absorption refrigeration machines", *Energy Int. J.*, Vol. 33, pp. 890-907.

Tsatsaronis, G., 1999a, "Strengths and limitations of exergy analysis", *Thermodynamic optimization of complex energy systems*, Bejan, A. and Mamut, E., eds., Dordrecht: Kluwer Academic Publishers, pp. 93–100.

Tsatsaronis, G., 1999b, "Design optimization using exergoeconomics", *Thermodynamic optimization of complex energy systems*, Bejan, A. and Mamut, E., eds., Dordrecht: Kluwer Academic Publishers, pp.101–117.

Tsatsaronis, G., Kelly, S. and Morosuk, T., 2006, "Endogenous and exogenous exergy destruction in thermal systems", *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Chicago, USA, CD-ROM, file 2006-13675.

Tsatsaronis, G. and Morosuk, T., 2007, "Advanced exergoeconomic evaluation and its application to compression refrigeration machines", *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Seattle, USA, CD-ROM, file 2007-41202.

Tsatsaronis, G. and Park, M.H., 2002, "On avoidable and unavoidable exergy destructions and investment costs in thermal systems", *Energy Conversion and Management*, Vol. 43, pp.1259–1270.