Advanced thermodynamic (exergetic) analysis

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Abstract. Exergy analysis is a powerful tool for developing, evaluating and improving an energy conversion system. However, the lack of a formal procedure in using the results obtained by an exergy analysis is one of the reasons for exergy analysis not being very popular among energy practitioners. Such a formal procedure cannot be developed as long as the interactions among components of the overall system are not being taken properly into account. Splitting the exergy destruction into unavoidable and avoidable parts in a component provides a realistic measure of the potential for improving the thermodynamic efficiency of this component. Alternatively splitting the exergy destruction into endogenous and exogenous parts provides information on the interactions among system components. Distinctions between avoidable and unavoidable exergy destruction on one side and endogenous and exogenous exergy destruction on the other side allow the engineer to focus on the thermodynamic inefficiencies that can be avoided and to consider the interactions among system components. The avoidable endogenous and the avoidable exogenous exergy destruction provide the best guidance for improving the thermodynamic performance of energy conversion systems.

1. Introduction
For the conventional exergetic evaluation of the $k$-th component of a system, the following variables are used [1-3]:

- The exergy destruction rate depends on the mass flow rate through the component and on the specific entropy generation within it:
  \[ \dot{E}_{D,k} = T_0 s_{gen,k} = T_0 \dot{m}_k s_{gen,k} \]  
  (1)

- The exergetic efficiency is the ratio between exergy of product and exergy of fuel
  \[ \varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}. \]  
  (2)

- The exergy destruction ratio is defined by
  \[ y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,\text{tot}}} \]  
  (3)

The exergy balance for the $k$-th component is
\[ \dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \]  
(4)
The advantages of exergetic analyses have been discussed in many previous publications. However, a conventional exergetic analysis cannot evaluate the mutual interdependencies among the system components neither the real potential for improving the components. This becomes possible in an advanced exergetic analysis [2,4-8], in which the exergy destruction in each component is split into endogenous and exogenous parts and avoidable and unavoidable parts. Finally a combination of these two splitting approaches provides the designer and operator of an energy conversion system with unambiguous and valuable detailed information with respect to options for improving the overall efficiency. These splittings improve the accuracy of exergy analysis and our understanding of the formation of thermodynamic inefficiencies, and facilitate the performance of exergy-based (exergoeconomic and exergoenvironmental) analyses.

2. Definitions

2.1. Endogenous and exogenous parts of exergy destruction
The total exergy destruction within the kth component is split into endogenous and exogenous parts \( \dot{E}_{D,k} = \dot{E}^N_{D,k} + \dot{E}^E_{D,k} \). Here \( \dot{E}^N_{D,k} \) is the endogenous part of exergy destruction, associated only with the irreversibilities occurring within the kth component when all other components operate in an ideal way and the component being considered operates with its current efficiency. \( \dot{E}^E_{D,k} \) is the exogenous part of exergy destruction in the kth component and is caused within the kth component also by the irreversibilities that occur within the remaining components.

2.2. Unavoidable and avoidable parts of exergy destruction
Only a part of the exergy destruction rate within a component can be avoided. The exergy destruction rate that cannot be reduced due to technological limitations such as availability and cost of materials and manufacturing methods is the unavoidable (\( \dot{E}^{UN}_{D,k} \)) part of the exergy destruction. The remaining part represents the avoidable (\( \dot{E}^{AV}_{D,k} \)) part of the exergy destruction. Thus, splitting the exergy destruction into unavoidable and avoidable parts in the kth component \( \dot{E}_{D,k} = \dot{E}^{UN}_{D,k} + \dot{E}^{AV}_{D,k} \) provides a realistic measure of the potential for improving the thermodynamic efficiency of a component.

2.3. Combination of the two splittings
By combining the concepts mentioned in the two previous sections, we obtain the unavoidable endogenous exergy destruction and subsequently the avoidable endogenous, the unavoidable exogenous and the avoidable exogenous parts of exergy destruction within the kth component.

The endogenous unavoidable (\( \dot{E}^{EN,UN}_{D,k} \)) part of the exergy destruction cannot be reduced because of technical limitations related to the kth component. The exogenous unavoidable (\( \dot{E}^{EX,UN}_{D,k} \)) part of the exergy destruction cannot be reduced because of technical limitations in the other components of the overall system for the given structure. The endogenous avoidable (\( \dot{E}^{EN,AV}_{D,k} \)) part of the exergy destruction can be reduced by improving the efficiency of the kth component. The exogenous avoidable (\( \dot{E}^{EX,AV}_{D,k} \)) part of the exergy destruction can be reduced by a structural improvement of the overall system or by improving the efficiency of the remaining components and of course by improving the efficiency of the kth component.

3. Calculations and results

3.1. Theoretical system
To easily demonstrate the concepts introduced in the previous sections, we use first a theoretical energy conversion system consisting of three components A, B and C in series (Figure 1) for which the assumptions given in the same figure apply. None of these assumptions is necessary for applying
an advanced exergy analysis. Note that the exergetic efficiencies $\varepsilon_A$, $\varepsilon_B$ and $\varepsilon_C$ can be varied independently from each other.

The analysis is conducted using either of the following two conditions: $\dot{E}_{P,\text{tot}} = \text{const}$ or $\dot{E}_{F,\text{tot}} = \text{const}$. In this paper we discuss among others how these conditions affect the results obtained from an advanced exergetic analysis.

### 3.2. Endogenous and exogenous parts of the exergy destruction

The equations for estimating the values of the total exergy destruction ($\dot{E}_{D,k}$) as well as the endogenous exergy destruction ($\dot{E}_{EN,k}$) within the $k$th component are given in Table 1. The case $\dot{E}_{P,\text{tot}} = \text{const}$ has been described in detail in [2,8].

The product of the overall theoretical system $\dot{E}_{P,\text{tot}}$ can be expressed as a function of (a) the fuel to the overall system, and (b) the exergetic efficiencies of the components $\dot{E}_{P,\text{tot}} = \dot{E}_{F,\text{tot}} \cdot \varepsilon_A \cdot \varepsilon_B \cdot \varepsilon_C$. Using this equation, which is not a general one, we obtain, as expected, the same equations for calculating $\dot{E}_{D,k}$ and $\dot{E}_{EN,k}$ estimated at either $\dot{E}_{P,\text{tot}} = \text{const}$ or $\dot{E}_{F,\text{tot}} = \text{const}$.

### 3.3. Unavoidable and avoidable parts of the exergy destruction

The unavoidable part of the exergy destruction in the $k$th component can be determined by calculating the exergy destruction for the overall system under the assumption that each component operates with its unavoidable thermodynamic inefficiency. For the system shown in Fig. 1, the value $\dot{E}_{D,\text{tot}}$ can be calculated by

**Table 1.** Equations for calculating $\dot{E}_{D,k}$ and $\dot{E}_{EN,k}$ for the theoretical energy conversion system shown in Fig. 1 at $\dot{E}_{P,\text{tot}} = \text{const}$ and $\dot{E}_{F,\text{tot}} = \text{const}$.

| Component | $\dot{E}_{P,\text{tot}} = \text{const}$ | $\dot{E}_{F,\text{tot}} = \text{const}$ |
|-----------|--------------------------------------|--------------------------------------|
|           | $\dot{E}_{D,k} = \dot{E}_{P,\text{tot}} \frac{1}{\varepsilon_A} \left( 1 - \frac{1}{\varepsilon_A} \right)$ | $\dot{E}_{D,k} = \dot{E}_{F,\text{tot}} \frac{1}{\varepsilon_A} \left( 1 - \frac{1}{\varepsilon_A} \right)$ |
| A         | $\dot{E}_{EN,k} = \dot{E}_{P,\text{tot}} \frac{1}{\varepsilon_A} \left( 1 - \frac{1}{\varepsilon_A} \right)$ | $\dot{E}_{EN,k} = \dot{E}_{F,\text{tot}} \frac{1}{\varepsilon_A} \left( 1 - \frac{1}{\varepsilon_A} \right)$ |
|           | where $\varepsilon_A < 1$ and $\varepsilon_B = \varepsilon_C = 1$ | $\dot{E}_{D,A} = \dot{E}_{F,\text{tot}} \left( 1 - \varepsilon_A \right)$ |
|           |                                       | $\dot{E}_{D,A} = \dot{E}_{F,\text{tot}} \frac{1}{\varepsilon_A} \left( 1 - \frac{1}{\varepsilon_A} \right)$ |
| B         | $\dot{E}_{D,B} = \dot{E}_{P,\text{tot}} \frac{1}{\varepsilon_B} \left( 1 - \frac{1}{\varepsilon_B} \right)$ | $\dot{E}_{D,B} = \dot{E}_{F,\text{tot}} \frac{1}{\varepsilon_B} \left( 1 - \frac{1}{\varepsilon_B} \right)$ |
|           | where $\varepsilon_B < 1$ and $\varepsilon_C = \varepsilon_A = 1$ | $\dot{E}_{D,B} = \dot{E}_{F,\text{tot}} \left( 1 - \varepsilon_B \right)$ |
|           |                                       | where $\varepsilon_B < 1$ and $\varepsilon_A = \varepsilon_C = 1$ |
| C         | $\dot{E}_{D,C} = \dot{E}_{P,\text{tot}} \frac{1}{\varepsilon_C} \left( 1 - \frac{1}{\varepsilon_C} \right)$ | $\dot{E}_{D,C} = \dot{E}_{F,\text{tot}} \frac{1}{\varepsilon_C} \left( 1 - \frac{1}{\varepsilon_C} \right)$ |
|           | $\dot{E}_{D,C} = \dot{E}_{F,\text{tot}} \left( 1 - \varepsilon_C \right)$ | $\dot{E}_{D,C} = \dot{E}_{F,\text{tot}} \frac{1}{\varepsilon_C} \left( 1 - \frac{1}{\varepsilon_C} \right)$ |
|           | where $\varepsilon_C < 1$ and $\varepsilon_A = \varepsilon_B = 1$ | where $\varepsilon_C < 1$ and $\varepsilon_A = \varepsilon_B = 1$ |
or if \( \dot{E}_{P,\text{tot}} = \text{const} \)

\[
\dot{E}_{D,\text{tot}}^{\text{UN}} = \dot{E}_{P,\text{tot}} \left[ \frac{1}{\varepsilon_C^{\text{UN}}} \left( \frac{1}{\varepsilon_B^{\text{UN}}} - 1 \right) + \frac{1}{\varepsilon_A^{\text{UN}}} \left( \frac{1}{\varepsilon_B^{\text{UN}}} - 1 \right) + \left( \frac{1}{\varepsilon_C^{\text{UN}}} - 1 \right) \right] 
\]

(6a)

and if \( \dot{E}_{F,\text{tot}} = \text{const} \)

\[
\dot{E}_{D,\text{tot}}^{\text{UN}} = \dot{E}_{F,\text{tot}} \left[ (1 - \varepsilon_A^{\text{UN}}) + \varepsilon_A^{\text{UN}} (1 - \varepsilon_B^{\text{UN}}) + \varepsilon_A^{\text{UN}} \varepsilon_B^{\text{UN}} (1 - \varepsilon_C^{\text{UN}}) \right] 
\]

(6b)

Here \( \varepsilon_k^{\text{UN}} \) (where \( k = A, B, C \)) denotes the maximum achievable exergetic efficiency of the \( k \)-th component in the foreseeable future.

3.4. Combining the two options for splitting the exergy destruction

The endogenous unavoidable part of the exergy destruction (\( \dot{E}_{D,k}^{\text{EN,UN}} \)) is the exergy destruction occurring within the \( k \)-th component when this component operates at its maximal attainable efficiency (\( \varepsilon_k^{\text{UN}} \)) while all other components operate in an ideal way. For the theoretical system in Fig. 1 we write:

for component A

\[
\dot{E}_{D,A}^{\text{EN,UN}} = \dot{E}_{P,\text{tot}} \left( \frac{1}{\varepsilon_A^{\text{UN}}} - 1 \right) 
\]

(7a)

or

\[
\dot{E}_{D,A}^{\text{EN,UN}} = \dot{E}_{F,\text{tot}} (1 - \varepsilon_A^{\text{UN}}) 
\]

(7b)

for component B

\[
\dot{E}_{D,B}^{\text{EN,UN}} = \dot{E}_{P,\text{tot}} \left( \frac{1}{\varepsilon_B^{\text{UN}}} - 1 \right) 
\]

(8a)

or

\[
\dot{E}_{D,B}^{\text{EN,UN}} = \dot{E}_{F,\text{tot}} (1 - \varepsilon_B^{\text{UN}}) 
\]

(8b)

and for component C

\[
\dot{E}_{D,C}^{\text{EN,UN}} = \dot{E}_{P,\text{tot}} \left( \frac{1}{\varepsilon_C^{\text{UN}}} - 1 \right) 
\]

(9a)

or

\[
\dot{E}_{D,C}^{\text{EN,UN}} = \dot{E}_{F,\text{tot}} (1 - \varepsilon_C^{\text{UN}}) 
\]

(9b)

The equations obtained for the values of \( E_{D,k}^{\text{EN,UN}} \) (Table 1) for the theoretical system (Fig.1), assuming that either \( \dot{E}_{P,\text{tot}} = \text{const} \) or \( \dot{E}_{F,\text{tot}} = \text{const} \), are identical, as it can easily be shown using the relationship \( \dot{E}_{P,\text{tot}} = \dot{E}_{F,\text{tot}} \cdot \varepsilon_A \cdot \varepsilon_B \cdot \varepsilon_C \). This means that for the theoretical system (when the exergy of product of the previous component is equal to the exergy of fuel of the following component) the initial assumptions for the advanced exergetic analysis (\( \dot{E}_{P,\text{tot}} = \text{const} \) or \( \dot{E}_{F,\text{tot}} = \text{const} \)) do not affect the obtained results. Similar conclusions can be found for the values of \( E_{D,k}^{\text{UN,EN}} \).

4. Real systems

For real energy conversion systems there are only very few examples where the exergy of product of the previous component is equal to the exergy of fuel of the following component (for example, the
connection between electrical motor and compressor, or between expander and electrical generator).

Usually, the exergy of product of the previous component is not equal to the exergy of fuel of the
following component because the definitions of the exergy of product and exergy of fuel depend on
the purpose of the \( k \) th component and are independent of the interconnections among the components
[1,9].

4.1. Endogenous and exogenous parts of the exergy destruction

For splitting the exergy destruction into endogenous/exogenous parts using the approach of the
thermodynamic cycles, we apply the following procedure [6-8,10,11]: (a) We initially create a so-
called theoretical cycle (theoretical process), and (b) we calculate the values of \( \dot{E}_{D,k}^{EN} \) using so-called
hybrid cycles (hybrid processes).

For the theoretical cycle, the theoretical operational conditions for each component should
correspond to the following assumptions: \( E_{D,k}^{th} = 0 \) (if possible, for example, for compressors, pumps
and turbines assuming that their isentropic efficiencies are equal to 1), or otherwise \( E_{D,k}^{th} = \min \) (for
heat exchangers if the minimal temperature difference equal to 0). In order to fulfil the theoretical
conditions for the components with chemical reactions, a more complex procedure (described in detail
in [11]) is used. Note that the theoretical process cannot be free of exergy destruction.

In each one of the hybrid cycles there is only one component that operates with its real efficiency,
whereas all other components operate as in the theoretical cycle.

The detailed methodology of splitting the exergy destruction into endogenous/exogenous parts is
given: (a) for refrigeration machines in [6,10], and (b) for power systems in [7,11,12].

4.2. Unavoidable and avoidable parts of the exergy destruction

For splitting the exergy destruction into unavoidable and avoidable parts, it is necessary to simulate a
process within the \( k \) th component assuming conditions that just cannot be realized in the foreseeable
future. According to the methodology described in [4,5,7,8,11,12] each component should be
simulated in isolation from the overall system. The value obtained from such a simulation is

\[
\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}^{\text{real}} \left( \frac{\dot{E}_{D,k}^{UN}}{E_{P,k}^{\text{UN}}} \right)
\]

and, finally the value of the unavoidable exergy destruction within the \( k \) th component is calculated by

\[
\dot{E}_{D,k}^{\text{UN}} = \dot{E}_{P,k}^{\text{real}} \left( \frac{\dot{E}_{D,k}^{UN}}{E_{P,k}^{\text{UN}}} \right)
\]

4.3. Combining the two options for splitting the exergy destruction

In order to split the exergy destruction within the \( k \) th component into unavoidable endogenous,
unavoidable exogenous, avoidable endogenous, and avoidable exogenous parts, we need a
methodology for calculating only one term: the unavoidable endogenous exergy destruction

\[
\dot{E}_{D,k}^{\text{UN,EN}} = \dot{E}_{P,k}^{\text{EN}} \left( \frac{\dot{E}_{D,k}^{UN}}{E_{P,k}^{\text{EN}}} \right)
\]

Other terms can be calculated easily as

\[
\begin{align*}
\dot{E}_{D,k}^{\text{UN,EX}} &= \dot{E}_{D,k}^{\text{UN}} - \dot{E}_{D,k}^{\text{UN,EN}} \\
\dot{E}_{D,k}^{\text{AV,EX}} &= \dot{E}_{D,k}^{\text{AV}} - \dot{E}_{D,k}^{\text{AV,EN}}
\end{align*}
\]
4.4. Effect of assumption: $\dot{E}_{P,\text{tot}} = \text{const}$ or $\dot{E}_{F,\text{tot}} = \text{const}$

Through the previous discussions the reader could see that for splitting the exergy destruction into unavoidable/avoidable parts, the assumption $\dot{E}_{P,\text{tot}} = \text{const}$ or $\dot{E}_{F,\text{tot}} = \text{const}$ does not play any role because each component should be considered in isolation. This assumption is, however, important when splitting the exergy destruction into endogenous/exogenous parts because every time the overall energy conversion system should be simulated and, in order to keep constant the product (or fuel) of the overall system for the theoretical or hybrid operation conditions, the mass flow rate(s) of the working fluid(s) are different for each simulation. Therefore the value of the endogenous exergy destruction will also depend on the assumption $\dot{E}_{P,\text{tot}} = \text{const}$ or $\dot{E}_{F,\text{tot}} = \text{const}$.

This is demonstrated by using two energy conversion systems as academic examples: (a) A system without a chemical reaction: a vapor-compression refrigeration machine, and (b) a system including a chemical reaction: an open-cycle gas-turbine system.

5. Refrigeration machine

The schematic of a simple vapor-compression refrigeration machine is shown in Figure 2. The thermodynamic data of the real cycle of this refrigeration machine are given in Table 2. The results from the conventional exergetic analysis are given in Table 3. State 0 for the exergy analysis is: $T_0=20^\circ\text{C}$ and $p_0=1\text{bar}$.

![Figure 2. A vapor-compression refrigeration machine.](image)

### Table 2. Thermodynamic data for the real cycle of the refrigeration machine shown in Figure 2.

| Stream | Working fluid | $m$ [kg/s] | $T$ [°C] | $p$ [bar] | $e_{ph}^\text{in}$ [kJ/kg] |
|--------|---------------|------------|----------|-----------|--------------------------|
| 1      | R717          | 0.092      | -25      | 1.52      | 67.49                    |
| 2      | (Ammonia)     | 0.092      | 153      | 11.67     | 393.20                   |
| 3      |               | 0.092      | 30       | 11.67     | 296.10                   |
| 4      |               | -25        | 1.52     | 264.90    |                          |
| 5      | Water         | 6.450      | 20       | 1.0       | 0                        |
| 6      | Water         | 6.450      | 25       | 1.0       | 0.18                     |
| 7      | Air           | 9.941      | -5       | 1.0       | 1.14                     |
| 8      | Air           | 9.941      | -15      | 1.0       | 2.29                     |

### Table 3. Conventional exergetic analysis and some data used in an advanced exergetic analysis for the compression refrigeration machine.

| Component | Conventional exergetic analysis | Advanced exergetic analysis |
|-----------|----------------------------------|-----------------------------|
|           | $\dot{E}_{F,k}$ [kW] | $\dot{E}_{P,k}$ [kW] | $\dot{E}_{D,k}$ [kW] | $\dot{E}_{F,k}^{\text{UN}}/\dot{E}_{P,k}^{\text{UN}}$ [kW] | $\dot{E}_{D,k}^{\text{EN}}/\dot{E}_{P,k}^{\text{EN}}$ [kW] |
| CM        | 34.90                          | 29.92                        | 4.98                        | 0.042                        | 3.48                        |
| CD        | 8.92                           | 1.14                         | 7.78                        | 2.407                        | 4.59                        |
| TV        | 21.82                          | 18.95                        | 2.87                        | 0.114                        | 1.35                        |
| EV        | 18.14                          | 11.41                        | 6.73                        | 0.207                        | 6.72                        |
| total     | 34.90                          | 11.41                        | 22.36                       | 0.042                        | 3.48                        |

6
The exergy destruction within each component of the open-cycle gas turbine system is calculated according to Eq.(4): \[ \hat{E}_{D,AC} = W_{AC} - (\hat{E}_2 - \hat{E}_1), \hat{E}_{D,CC} = (\hat{E}_3 - \hat{E}_4), \quad \hat{E}_{D,GT} = (\hat{E}_4 - \hat{E}_5) - W_{GT}. \]

The detailed methodology for splitting the exergy destruction into endogenous/exogenous and unavoidable/avoidable parts is given in Ref. [11]. The results obtained from the advanced exergetic analysis using both assumptions (\(E_{P,\text{tot}} = \text{const}\) or \(E_{F,\text{tot}} = \text{const}\)) are given in Table 5.

As mentioned above, the values of the unavoidable exergy destruction within the components of the vapor-compression refrigeration machine are independent of the assumption made for the analysis. The value of \(E_{D,k}^{\text{EN}}\) strongly depends on the assumption, because of the different mass flow rates of the working fluids.

### 6. Gas-turbine system

The open-cycle gas turbine system shown in Fig.3 has been used as an academic example in Ref. [11]. The thermodynamic data of the real cycle of this gas-turbine system are given in Table 4. The results from the conventional exergetic analysis are given in Table 5. State 0 for the exergy analysis is: \(T_0=25^\circ\text{C}\) and \(p_0=1.013\) bar.

The exergy destruction within each component of the open-cycle gas turbine system is calculated according to Eq.(4): \[ \hat{E}_{D,AC} = W_{AC} - (\hat{E}_2 - \hat{E}_1), \quad \hat{E}_{D,CC} = (\hat{E}_3 - \hat{E}_4), \quad \hat{E}_{D,GT} = (\hat{E}_4 - \hat{E}_5) - W_{GT}. \]

The detailed methodology for splitting the exergy destruction into endogenous/exogenous and unavoidable/avoidable parts is given in Ref. [11]. The results obtained from the advanced exergetic analysis using both assumptions (\(E_{P,\text{tot}} = \text{const}\) or \(E_{F,\text{tot}} = \text{const}\)) are given in Table 5.
7. Conclusions
An option of an advanced exergy-based (exergetic, exergoeconomic and exergoenvironmental) analysis is splitting the total exergy destruction occurring within each component of an energy conversion system into endogenous/exogenous and unavoidable/avoidable parts and combining the results to focus on the endogenous avoidable and the exogenous avoidable parts of exergy destruction. With this approach the potential for improving each system component is identified and the priorities, according to which the design of components should be modified, are established. This information cannot be provided by conventional exergy-based analyses.

In the earlier publications related to the development and first applications of the advanced exergy-based analyses, for splitting the exergy destruction into endogenous/exogenous part, we used the assumption that the exergy of product of the overall system remains constant. Here we compared the results received under this assumption with the results obtained under the assumption that the fuel of the overall system remains constant. The deviations in the values of endogenous exergy destruction are significant. Further investigations are needed to clarify this issue.

8. Nomenclature

\[ \begin{align*}
\dot{E} & \quad \text{exergy rate [W]} \\
\dot{m} & \quad \text{mass flow rate [kg/s]} \\
p & \quad \text{pressure [bar]} \\
\dot{Q} & \quad \text{heat rate [W]} \\
T & \quad \text{temperature [ºC]} \\
\dot{W} & \quad \text{power [W]} \\
y & \quad \text{exergy destruction ratio [%]} \\
\varepsilon & \quad \text{exergetic efficiency [%]} \\
\eta & \quad \text{energetic efficiency [%]} \\
AV & \quad \text{avoidable} \\
EN & \quad \text{endogenous} \\
EX & \quad \text{exogenous} \\
UN & \quad \text{unavoidable}
\end{align*} \]

\[ \begin{align*}
D & \quad \text{exergy destruction} \\
F & \quad \text{fuel} \\
k & \quad \text{kth component} \\
L & \quad \text{exergy losses} \\
P & \quad \text{exergy of product} \\
tot & \quad \text{total} \\
AC & \quad \text{air compressor} \\
CC & \quad \text{combustion chamber} \\
CD & \quad \text{condenser} \\
CM & \quad \text{compressor} \\
EV & \quad \text{evaporator} \\
GT & \quad \text{gas turbine} \\
TV & \quad \text{throttling valve}
\end{align*} \]

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