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Advanced exergetic analysis of a refrigeration system for liquefaction of natural gas

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ABSTRACT

During the last years the total cost of LNG technology has decreased significantly due to improvements of the liquefaction process. However, many liquefaction plants that are still in operation use a three-cascade refrigeration system. In this paper, an advanced exergetic analysis is applied to better understand the operation of a three-cascade refrigeration system for liquefaction of natural gas. In an advanced exergetic analysis, the exergy destruction within a plant component is split into its endogenous/exogenous and unavoidable/avoidable parts. With the aid of this analysis, the potential for improving the thermodynamic efficiency of components and the overall system as well as the interactions among components and their effect on the exergy destruction within each component are estimated. This paper demonstrates some capabilities associated with an advanced exergetic analysis.

KEYWORDS

LNG, liquefaction, cascade refrigeration machine, exergetic analysis, advanced exergetic analysis.

1. INTRODUCTION

Liquefied Natural Gas (LNG) is expected to contribute more in future than in the past to the overall energy supply in the world. The advantages of using LNG as well as problems related to all stages of LNG technology (liquefaction process, transport and regasification process) are discussed frequently in the literature; some new and important data are summarized in [1-3].

Worldwide, there are 26 existing liquefaction (export) terminals, located on or off shore, in 15 countries (the start up date of the earliest liquefaction terminal is given in parenthesis): USA (1969), Libya (1970), Algeria (1971), Brunei (1972), Indonesia (1977), United Arab Emirates (1977), Malaysia (1983), Australia (1989), Qatar (1997), Nigeria (1999), Trinidad and Tobago(1999), Oman (2000),Egypt (2004), Equatorial Guinea (2007), Norway, (2007) [1,2].

During the last years the total cost of LNG technology has decreased significantly due to improvements of the liquefaction process:Instead of the classical three-cascade refrigeration system used in the first liquefaction terminals, new schematics with different mixtures as working fluids are developed. Examples include, (a) the single flow mixed refrigerant process, where the mixed refrigerant, made up of nitrogen, methane, ethane, propane and isopentane, is compressed using a single compression train, and (b) the propane precooled mixed refrigerant process where precooling is achieved by a multi-stage propane cycle, while liquefaction and subcooling are accomplished by a two-stage mixed refrigerant cycle, which is so far the most common process. Other processes have also been developed, but are not yet in operation [2,3].

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Many liquefaction plants, based on a three-cascade refrigeration system, are in operation in the world. The liquefaction process requires large energy consumption. Improving the thermodynamic efficiency of these systems can lead to a decrease in the cost of the generated LNG.

In this paper, a three-cascade refrigeration system for liquefaction of natural gas is analyzed using conventional and advanced exergetic analyses. The purpose of an exergy-based diagnosis is to identify the most inefficient components and to recommend the replacement of old components with new ones.

2. THREE-CASCADE REFRIGERATION SYSTEM FOR LIQUEFACTION OF NATURAL GAS

The schematic of the three-cascade refrigeration system used for liquefaction of natural gas is shown in Figure 1. The operating conditions for the liquefaction plant as well as the environmental conditions are based on generalized data obtained from the existing export terminals [4]. Some initial data and assumptions made for the simulation are given in Table 1. The simulation of a three-cascade refrigeration system is relatively difficult because many factors should be taken into account simultaneously. More details and the assumptions used for the analysis are given in[5].

Thermodynamic data for the material streams are given in Table 2. The following simplifications, which do not significantly affect the results obtained from the energetic and exergetic analyses, were used:

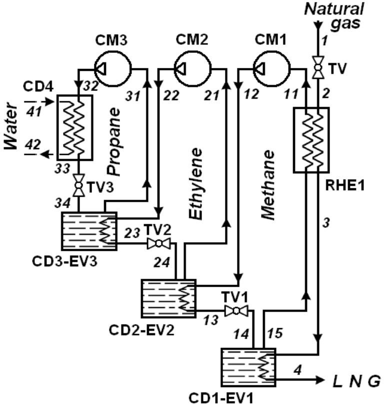

Fig.1: Three-cascade refrigeration system used for liquefaction of natural gas.

TABLE 1
INITIAL DATA AND ASSUMPTIONS

Natural gas	Value
Composition	CH_4
Mass flow rate	1 kg/s
Temperature of natural gas at state 1	50°C
Pressure of natural gas at state 1	51 bar
Temperature of liquefaction	−110°C
Heat exchangers	
Pressure drop (Δp) in side pipes	3%
Temperature difference, ΔT in CD-EV	10 K
Cooling water	
Inlet temperature (T_{41})	35°C
Inlet pressure (p_{41})	2 bar
Outlet temperature (T_{42})	42°C
Outlet pressure (p_{42})	1.5 bar
Reference state for the exergetic analysis	
Temperature (T_0)	35°C
Pressure (p_0)	1 bar

- Thermodynamic states 4 (natural gas), 13 (methane), 23 (ethylene), and 33 (propane) are saturated liquid, and
- States 15 (methane), 21 (ethylene), and 31 (propane) are saturated vapor. To estimate the mass flow rates of the working fluids, the following energy balances are used

$$\dot{m}_{methane} = \frac{\dot{m}_{NG}\left(h_3 - h_4\right)}{h_{15} - h_{14}} \tag{1}$$

$$\dot{m}_{ethylene} = \frac{\dot{m}_{methane}\left(h_{12} - h_{13}\right)}{h_{21} - h_{24}} \tag{2}$$

$$\dot{m}_{propane} = \frac{\dot{m}_{ethylene}\left(h_{22} - h_{23}\right)}{h_{31} - h_{34}} \tag{3}$$

For the analysis, the mass flow rate of the LNG was assumed to be equal to 1 kg/s. This value is kept constant for the energetic analysis as well as for the conventional and advanced exergetic analyses.

From the energetic analysis we obtain for the

- heat rates : $\dot{Q}_{RHE1}$ = 365 kW, $\dot{Q}_{CD1-EV1}$ = 728 kW,
  $\dot{Q}_{CD2-EV2}$ = 1109 kW, $\dot{Q}_{CD3-EV3}$ = 2304 kW, $\dot{Q}_{CD4}$ = 3778 kW, and for the
- power: $\dot{W}_{CM1}$ = 381 kW, $\dot{W}_{CM2}$ = 1194 kW,

and $\dot{W}_{CM3}$ = 1475 kW.

The coefficient of performance of this three-cascade refrigeration system is calculated from

$$COP = \frac{\dot{H}_4 - \dot{H}_1}{\dot{W}_{CM1} + \dot{W}_{CM2} + \dot{W}_{CM3}}, \tag{4}$$

and is equal to 0.24. This value is low, but can be considered as acceptable for such a low-temperature refrigeration system.

3. CONVENTIONAL EXERGETIC ANALYSIS

Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable from an energy conversion system as this is brought into thermodynamic equilibrium with the thermodynamic environment while interacting only with this environment [6].

The total exergy associated with the j th material stream represents the sum of the physical and chemical exergies. Since no chemical reactions occur within components of the analyzed three-cascade refrigeration system, only the physical exergy $\dot{E}_j^{PH}$ associated with the j th material stream is considered

$$\dot{E}_j^{PH} = \dot{m}_j \cdot e_j^{PH} = \dot{m}_j \left[\left(h_j - h_0\right) - T_0\left(s_j - s_0\right)\right] \tag{5}$$

The subscript 0 refers to the property values of the same mass flow rate at temperature T_0 and pressure p_0 of the reference state.

In all components (except CD4) of the three-cascade refrigeration system either all temperatures are below the reference temperature T_0, or this temperature is crossed during system operation. In either case, the physical exergies of all states should be split into their thermal (e^T) and mechanical (e^M) exergy components (according to the approach presented in [7])

$$e_j^{PH} = \underbrace{\left[\left(h_j - h_{j,X}\right) - T_0\left(s_j - s_{j,X}\right)\right]_{p=const}}_{e^T} + \underbrace{\left[\left(h_{j,X} - h_{j,0}\right) - T_0\left(s_{j,X} - s_{j,0}\right)\right]_{T_0=const}}_{e^M} \tag{6}$$

TABLE 2
THERMODYNAMIC DATA FOR THE MATERIAL STREAMS AT REAL OPERATING CONDITIONS

Material stream	State	$\dot{m}$ (kg/s)	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg.K)	e^T (kJ/kg)	e^M (kJ/kg)	e^{PH} (kJ/kg)
NG	1	1.000	51.00	50.0	12.9	–1.951	0.9	615.7	616.6
NG	2		18.57	38.3	12.9	–1.450	0.04	462.1	462.1
LNG	3		18.03	–109	–351.9	–3.048	132.2	457.5	589.7
LNG	4		17.48	–111	–715.6	–5.277	459.5	452.7	912.3
Methane	11	1.419	11.60	–13	–97.5	–1.600	9.3	388.7	398.0
Methane	12		36.40	108	170.9	–1.333	18.9	565.3	584.1
Methane	13		35.31	–91	–610.7	–4.704	280.1	560.7	840.8
Methane	14		11.96	–120	–610.7	–4.574	407.3	393.4	800.7
Methane	15		11.96	–120	–354.5	–2.901	148.2	393.4	541.7
Ethylene	21	4.116	1.26	–100	–174.9	–0.815	57.1	21.0	78.1
Ethylene	22		24.01	109	115.2	–0.573	14.5	279.0	293.5
Ethylene	23		23.29	–23	–444.4	–2.608	84.1	276.5	360.6
Ethylene	24		1.26	–100	–444.4	–2.372	267.0	21.0	288.0
Propane	31	11.260	1.55	–32	537.9	2.423	13.4	25.0	38.4
Propane	32		17.65	70	668.8	2.469	19.1	136.0	155.1
Propane	33		16.62	49	333.3	1.440	0.9	135.8	136.7
Propane	34		1.55	–32	333.3	1.575	70.1	25.0	95.1
Water	41	129.300	2.00	35	146.8	0.505	0	0.1	0.1
Water	42		1.50	42	176.0	0.600	0.34	0.05	0.39
Reference states for the exergetic analysis									

Methane	0	–	1.00	35	21.5	0.078	0	0	0
Ethylene	0	–	1.00	35	14.0	0.052	0	0	0
Propane	0	–	1.00	35	647.9	2.905	0	0	0
Water	0	–	1.00	35	146.7	0.505	0	0	0

TABLE 3

DEFINITION OF THE EXERGY OF FUEL AND THE EXERGY OF PRODUCT FOR EACH COMPONENT IN THE SYSTEM.

Component	$\dot{E}_{F,k}$	$\dot{E}_{P,k}$
RHE1 1)	$\left(\dot{E}_{15}^{T}-\dot{E}_{11}^{T}\right)+\left(\dot{E}_{15}^{M}-\dot{E}_{11}^{M}\right)+\left(\dot{E}_{2}^{M}-\dot{E}_{3}^{M}\right)+\dot{E}_{2}^{T}$	$\dot{E}_{3}^{T}$
CM1 1)	$\dot{W}_{CM1}+\dot{E}_{11}^{T}$	$\left(\dot{E}_{12}^{M}-\dot{E}_{11}^{M}\right)+\dot{E}_{12}^{T}$
CD1-EV1 2)	$\left(\dot{E}_{14}^{T}-\dot{E}_{15}^{T}\right)+\left(\dot{E}_{14}^{M}-\dot{E}_{15}^{M}\right)+\left(\dot{E}_{3}^{M}-\dot{E}_{4}^{M}\right)$	$\dot{E}_{4}^{T}-\dot{E}_{3}^{T}$
TV1 2)	$\dot{E}_{13}^{M}-\dot{E}_{14}^{M}$	$\dot{E}_{14}^{T}-\dot{E}_{13}^{T}$
CM2 1)	$\dot{W}_{CM2}+\dot{E}_{21}^{T}$	$\left(\dot{E}_{22}^{M}-\dot{E}_{21}^{M}\right)+\dot{E}_{22}^{T}$
CD2-EV2 1)	$\left(\dot{E}_{24}^{T}-\dot{E}_{21}^{T}\right)+\left(\dot{E}_{24}^{M}-\dot{E}_{21}^{M}\right)+\left(\dot{E}_{12}^{M}-\dot{E}_{13}^{M}\right)+\dot{E}_{12}^{T}$	$\dot{E}_{13}^{T}$
TV2 2)	$\dot{E}_{23}^{M}-\dot{E}_{24}^{M}$	$\dot{E}_{24}^{T}-\dot{E}_{23}^{T}$
CM3 1)	$\dot{W}_{CM3}+\dot{E}_{31}^{T}$	$\left(\dot{E}_{32}^{M}-\dot{E}_{31}^{M}\right)+\dot{E}_{32}^{T}$
CD4 3,4)	$\left(\dot{E}_{32}^{T}-\dot{E}_{33}^{T}\right)-\left(\dot{E}_{32}^{M}-\dot{E}_{33}^{M}\right)+\left(\dot{E}_{41}^{M}-\dot{E}_{42}^{M}\right)$	$\dot{E}_{42}^{T}-\dot{E}_{41}^{T}$
TV3 1)	$\left(\dot{E}_{33}^{M}-\dot{E}_{34}^{M}\right)+\dot{E}_{33}^{T}$	$\dot{E}_{34}^{T}$
CD3-EV3 1)	$\left(\dot{E}_{34}^{T}-\dot{E}_{31}^{T}\right)+\left(\dot{E}_{34}^{M}-\dot{E}_{31}^{M}\right)+\left(\dot{E}_{22}^{M}-\dot{E}_{23}^{M}\right)+\dot{E}_{22}^{T}$	$\dot{E}_{23}^{T}$

1) The reference temperature T_0 is crossed during the operation in this component.

2) This component operates below the reference temperature T_0.

3) This component operates above the reference temperature T_0.

4) This component is in reality a dissipative component for which no exergetic efficiency should be defined.

TABLE 4

DATA OBTAINED FROM THE CONVENTIONAL EXERGETIC ANALYSIS

Component	$\dot{E}_{F,k}$ (kW)	$\dot{E}_{P,k}$ (kW)	$\dot{E}_{D,k}$ (kW)	y_k (%)	ε_k (%)
RHE1	208.5	132.2	76.3	2.50	63
CM1	394.3	277.5	116.8	3.83	70
CD1-EV1	372.5	327.4	45.1	1.49	88
TV1	237.3	180.5	56.8	1.86	76
CM2	1429.7	1122.0	307.7	10.09	79
CD2-EV2	897.3	397.6	499.7	16.38	44
TV2	1051.9	753.2	298.7	9.79	72
CM3	1626.5	1466.3	160.2	5.25	90
CD4	217.6	47.2	170.4	5.59	22
TV3	1247.6	779.9	467.7	15.34	63
CD3-EV3	708.3	346.0	362.3	11.88	49
Overall system	**3050.0**	**450.2**	**2561.7**	**83.99**	**15**

In Eq.(6) the point $X(T_0, p)$ is defined at the given pressure p of the jth stream and the temperature T_0 of the environment. The values of e_j^T, e_j^M and e_j^{PH} are given in Table 2.

An *exergy-based* thermodynamic *analysis* identifies the location, the magnitude, and the causes of thermodynamic inefficiencies, which are the *exergy destruction* $\dot{E}_{D,k}$ (due to irreversibilities within the system), and the *exergy loss* $\dot{E}_{L,k}$ (i.e., the exergy transfer to the environment). In an exergy analysis we calculate the exergy associated with each energy carrier (stream) in the overall system, the exergy destruction within each system component and process, and the *exergetic efficiency* ε_k (for each process, component, or system) [8]. Exergy loss is here associated with the overall system but not with a component [9] because each exergy stream exiting a component is considered either at the fuel or at the product side.

The exergy balance for the *k*th component is then

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \tag{7}$$

and for the overall system

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \sum_k \dot{E}_{D,k} + \dot{E}_{L,tot} \tag{8}$$

Central elements for the exergetic analysis are the general concepts of *fuel* ($\dot{E}_{F,k}$) and *product* ($\dot{E}_{P,k}$) introduced over 25 years ago [10] (instead of the concept of incoming/outgoing exergy which was used in earlier versions of the exergetic analysis): The *exergy of product* is the desired result (expressed in exergy terms) achieved by the system (e.g., the *k*th component) being considered, and the *exergy of fuel* is the exergetic resources expended to generate the exergy of the product. The definition of the exergy of fuel and the exergy of product for all system components as well as for the overall system that are given in Table 3, are consistent with the SPECO principle [11] while extending and complementing it: When the ambient temperature is crossed by a stream during the operation of a component, then it is not meaningful to use the exergy difference between inlet and outlet for this stream. In this case the exergy at the inlet of the stream crossing the ambient temperature belongs to the "fuel" while the exergy at the outlet belongs to the "product" of the component. For components operating entirely below the ambient temperature, it should be noted that the lower the temperature of a stream, the higher its thermal exergy.

For the exergetic evaluation, the following two variables are used:

- Exergetic efficiency

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \tag{9}$$

- Exergy destruction ratio y_k that relates the exergy destruction within the *k*th component to the fuel for the overall system

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}} \tag{10}$$

The results obtained from the conventional exergetic analysis of the three-cascade refrigeration machine are given in Table 4.

4. ADVANCED EXERGETIC ANALYSIS

The quality of the conclusions obtained from an exergetic analysis can be improved, when the exergy destruction in each (important) system component is split into unavoidable/avoidable and endogenous/exogenous parts. We call the analysis based on these procedures *advanced exergetic analysis*. All publications up to date in the field of the advanced exergy-based methods are summarized and generalized in [12,13], and for refrigeration machines in [14,15]. Options for splitting the exergy destruction within the *k*th component in an advanced exergy analysis are shown in Figure 2.

The *unavoidable* exergy destruction ($\dot{E}_{D,k}^{UN}$) cannot be further reduced due to technological limitations such as availability and cost of materials and manufacturing methods. The difference between total and unavoidable exergy destruction within a component is the *avoidable* exergy destruction that should be considered during the improvement procedure $\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN}$, where the value of the unavoidable exergy destruction within the *k*th component is calculated by

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}^{real} \left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN} \tag{11}$$

For calculating the value of $\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}} \right)^{UN}$, a system in which only unavoidable exergy destructions occur within each component should be simulated.

Endogenous exergy destruction ($\dot{E}_{D,k}^{EN}$) is the part of exergy destruction within a component obtained when all other components operate ideally and the component being considered operates with the same efficiency as in the real system. The *exogenous* part of the variable is the difference between the values of the variable being considered in the real system and in the endogenous case: $\dot{E}_{D,k}^{EX} = \dot{E}_{D,k} - \dot{E}_{D,k}^{EN}$. This splitting of the exergy destruction shows the interactions among different components of the same system.

To calculate the value of $\dot{E}_{D,k}^{EN}$ the following generalized methodology was developed:

Step 1: In the so-called *theoretical cycle*, the operating conditions for each component should correspond to either $\dot{E}_{D,tot} = 0$ (where it is possible) or to $\dot{E}_{D,tot} = min$ (for example in a heat exchanger with different heat capacity rates of the working fluids: In this case ΔT_{min}=0). In calculating the value of the endogenous exergy destruction in a component, we neglect the effect that the small exergy destruction within some theoretical heat exchangers has on these values.

Step 2: The endogenous part of the exergy destruction within the *k*th component is calculated through an analysis of the so-called *hybrid cycle*. The hybrid cycle represents the theoretical cycle with irreversibilities within the *k*th component only. The number of the hybrid cycles that should be created for the analysis is equal to the number of the components in the overall system.

For obtaining a deeper understanding of the interactions among components, the exogenous exergy destruction (as well as the exogenous unavoidable and the exogenous avoidable exergy destructions) within the *k*th component are split [16]

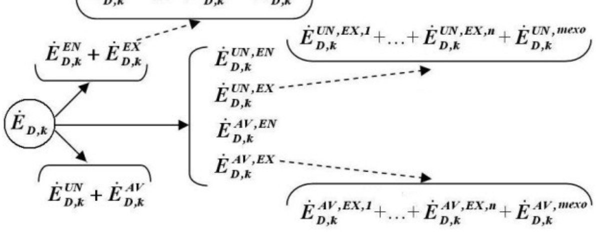

Fig2: Options for splitting the exergy destruction within the *k*th component in an advanced exergy analysis.

$$\dot{E}_{D,k}^{EX} = \sum_{\substack{r=1\\ r\neq k}}^{n} \dot{E}_{D,k}^{EX,r} + \dot{E}_{D,k}^{mexo} \qquad (12)$$

The value of $\dot{E}_{D,k}^{EX,r}$ represents the part of the exogenous exergy destruction within the *k*th component that is caused by the irreversibilities occurring within the *r*th component. The remaining part we call *mexogenous exergy destruction* (from mixed exogenous exergy destruction) within the *k*th component, $\dot{E}_{D,k}^{mexo}$, and is caused by the combined interaction of three or more components.

The two concepts of splitting the exergy destruction (into unavoidable/avoidable and endogenous/exogenous parts) should be combined. Thus, the following important variables for the design procedure and for the evaluation of a system can be estimated:

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

To calculate the above variables, first the value $\dot{E}_{D,k}^{UN,EN}$ is calculated:

$$\dot{E}_{D,k}^{UN,EN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN} \qquad (13)$$

where the value $\dot{E}_{P,k}^{EN}$ is obtained simultaneously with the value $\dot{E}_{D,k}^{EN}$ (from the analysis of a hybrid cycle for each system component).

Table 5
Real, unavoidable, and theoretical operation conditions

Parameter	Real conditions	Unavoidable conditions	Theoretical conditions
Pressure drop, Δp	3 %	0.5 %	0 %
Min. temperature difference in CD-EV, ΔT	10 K	4 K	0 K
Isentropic efficiencies for compressors, η_{CM}	CM1 - 64% CM2 - 70% CM3 - 88%	CM1 - 95% CM2 -95% CM3 -95%	CM1 - 100% CM2 -100% CM3 -100%
Temperature at CD4	50°C	44°C	42°C
Processes 13−14, 23−24 and 33−34	Throttling	Throttling	Isentropic expansion
Stream 41	T_{41} = 35ºC, p_{41} = 2.00 bar		
Stream 42	T_{42} = 42ºC, p_{42} = 1.50 bar		

Table 6
Thermodynamic data for the three-stage refrigeration machine having only unavoidable irreversibilities

Material stream	State	$\dot{m}$ (kg/s)	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg.K)	e^T (kJ/kg)	e^M (kJ/kg)	e^{PH} (kJ/kg)
NG	1	1.000	51.00	50	12.9	-1.951	0.9	615.7	616.6
NG	2		18.12	38	12.9	-1.437	0.1	458.2	458.3
LNG	3		18.03	-110	-354.2	-3.062	134.2	457.5	591.7
LNG	4		17.94	-110	-712.7	-5.259	453.2	456.7	909.9
Methane	11	1.425	15.31	-10	-96.2	-1.734	8.4	432.1	440.5
Methane	12		36.40	54	36.3	-1.713	1.4	565.3	566.7
Methane	13		36.22	-90	-605.3	-4.676	273.1	564.5	837.6
Methane	14		15.00	-114	-605.3	-4.579	374.8	432.8	807.6
Methane	15		15.00	-114	-353.8	-2.998	139.6	432.8	572.4
Ethylene	21	3.364	1.74	-94	-169.4	-0.876	51.9	50.4	102.3
Ethylene	22		24.01	57	17.5	-0.847	1.4	279.0	280.4
Ethylene	23		23.89	-5	-441.3	-2.595	81.5	278.6	360.1
Ethylene	24		1.74	-94	-441.3	-2.393	247.5	50.3	297.8
Propane	31	6.844	2.11	-24	547.3	2.407	10.5	42.4	52.9
Propane	32		15.42	57	646.0	2.422	11.5	135.5	147.0
Propane	33		15.27	45	321.9	1.405	0.5	135.4	135.9
Propane	34		2.11	-24	321.9	1.502	63.7	42.5	106.2

$\dot{m}_{41} = \dot{m}_{42} =$ 75.90 kg/s.

The designer is guided to focus only on the endogenous avoidable and exogenous avoidable exergy destructions, i.e. on the potential for reducing the exergy destruction.

To identify priorities for improving components based on information obtained from an advanced exergetic analysis, we use the sum of the avoidable endogenous exergy destruction within the *k*th component and the avoidable exogenous exergy destructions within the remaining components caused by the *k*th component [13]

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{E}_{D,r}^{AV,EX,k} \qquad (14)$$

Table 5 shows the different operation conditions for the components of the three-cascade refrigeration machine: (a) Real, which has been used for the conventional exergetic analysis, (b) unavoidable, i.e. with a very high efficiency for each component (used for calculating the unavoidable exergy destruction), and (c) theoretical, used for creating the theoretical cycle and after that for calculating the endogenous exergy destruction.

Table 6 shows the thermodynamic data for the three-stage refrigeration machine having only unavoidable irreversibilities (Table 5).

Table 7 shows the theoretical operation conditions for the three-stage refrigeration machine. At these operating conditions $\dot{E}_{D,tot} = min$, i.e. $\dot{E}_{D,tot} = 542$ kW.

TABLE 7

THERMODYNAMIC DATA FOR THE THREE-STAGE REFRIGERATION MACHINE AT THEORETICAL OPERATION CONDITIONS.

Material stream	State	$\dot{m}$ (kg/s)	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg.K)	e^T (kJ/kg)	e^M (kJ/kg)	e^{PH} (kJ/kg)
NG	1	1.000	51.00	50	12.9	-1.951	0.9	615.7	616.6
NG	2		18.03	38	12.9	-1.435	0.1	457.4	457.5
LNG	3		18.03	-110	-354.6	-3.065	134.6	457.5	592.1
LNG	4		18.03	-110	-712.1	-5.256	451.9	457.5	909.4
Methane	11	1.365	18.03	-4	-85.3	-1.774	6.2	457.5	463.7
Methane	12		36.40	46	16.8	-1.774	0.5	565.3	565.8
Methane	13		18.03	-110	-616.6	-4.670	367.2	457.5	824.6
Methane	14		18.03	-110	-354.6	-3.065	134.6	457.5	592.1
Methane	15		18.03	-4	-85.3	-1.774	6.2	457.5	463.7
Ethylene	21	2.755	2.13	-90	-165.8	-0.913	48.7	68.6	117.3
Ethylene	22		24.01	46	-3.9	-0.913	0.3	279.0	279.3
Ethylene	23		24.01	-22	-440.6	-2.593	80.9	279.0	359.9
Ethylene	24		2.13	-90	-473.5	-2.593	258.4	68.7	327.1
Propane	31	4.766	2.27	-22	549.7	2.403	9.8	46.6	56.4
Propane	32		15	53	638.6	2.403	9.9	135.4	145.3
Propane	33		15	44	319.6	1.398	0.4	135.4	135.8
Propane	34		2.27	-22	297.3	1.398	66.9	46.6	113.5

$\dot{m}_{41} = \dot{m}_{42} = 52.02$ kg/s.

Table 8 summarizes the thermodynamic data for each hybrid cycle. Note that the thermodynamic data for the remaining material streams correspond to the theoretical operating conditions. The mass flow rates for each sub-cycle are also given in Table 8 for each hybrid cycle.

The values of $\left(\frac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}$ as well as the values of $\dot{E}_{P,k}^{EN}$ (which are necessary for Eq. (12)) are given in Table 9.

The detailed splitting of the exergy destruction values for each component is presented in Table 10.

4. RESULTS AND DISCUSSIONS

The results from the conventional exergetic analysis ($\dot{E}_{D,k}$ or y_k in Table 4) show that CD2-EV2, TV3, CD3-EV3, CM2, and TV2 are the most important components from the thermodynamic viewpoint.

These results are misleading to some extent because, for example, they suggest that we should try to reduce the exergy destruction within the components TV3 and TV2. However, as the results from the advanced exergetic analysis indicate (Table 10), the endogenous avoidable exergy destruction in all throttling valves is zero. This means that the exergy destruction within these components can be reduced only through changes in the remaining components or in the structure of the overall plant.

Also with respect to the relative importance of TV2 and TV3 we obtain misleading information from the conventional analysis, which suggests that TV3 is more important than TV2. The variable $\dot{E}_{D,k}^{AV,\Sigma}$ (Table 9), however, shows that TV2 is much more important than TV3.

From the advanced analysis we obtain the following additional information: Most of the exergy destruction in the components RHE, TV1, CD2-EV2, TV2, CD4 and TV3 is unavoidable (Table 10). Most of the exergy destruction in the components CM3, CD4, TV3 and CD3-EV3 is exogenous, i.e. it is caused by the interactions of the component being considered with the other components. Particularly for the components CD3-EV3 and CD2-EV2, the avoidable exogenous part of the exergy destruction is very high (last column in Table 10). Thus, the exergy destruction within these components can be reduced more effectively by improving the efficiency of the remaining components.

The variable $\dot{E}_{D,k}^{AV,\Sigma}$ (Table 9) indicates that, when we consider the interactions among components and only the avoidable part of exergy destruction, the most important components of the overall system are CM2, CD1-EV1, CM1 and CD2-EV2. Thus, we obtain a completely different picture from the advanced exergetic analysis than from the conventional one, and the picture from the advanced analysis is much closer to reality than the one from the conventional analysis. For example, the advanced analysis emphasizes the importance of compressors (CM1 and CM2) and reduces the importance of CD2-EV2 and CD3-EV3.

From the engineering point of view, CM1 and CM2 can be improved by selecting, for example, a rotary (rotating

TABLE 8

THERMODYNAMIC DATA FOR THE THREE-STAGE REFRIGERATION MACHINE WITH IRREVERSIBILITIES ONLY WITHIN THE *K*TH COMPONENT.

Material stream	State	$\dot{m}$ (kg/s)	p (bar)	T (°C)	h (kJ/kg)	s (kJ/kg.K)	e^T (kJ/kg)	e^M (kJ/kg)	e^{PH} (kJ/kg)
Within RHE 1 ($\dot{m}_{11-15}$ = 1.375 kg/s, $\dot{m}_{21-24}$ = 2.776 kg/s, $\dot{m}_{31-34}$ = 4.803 kg/s, $\dot{m}_{41-42}$ = 52.42 kg/s)									
NG	1	1.000	51.00	50	12.9	-1.951	0.9	615.7	616.6
NG	2		18.57	38	12.9	-1.450	0.1	462.0	462.1
LNG	3		18.03	-109	-351.9	-3.048	132.2	457.5	589.7
LNG	4		18.03	-110	-712.1	-5.256	451.9	457.5	909.4
Within CD1-EV1 ($\dot{m}_{21-24}$ = 3.022 kg/s, $\dot{m}_{31-34}$ = 5.229 kg/s, $\dot{m}_{41-42}$ = 57.07 kg/s)									
Methane	11	1.332	11.96	-4	-78.5	-1.544	6.2	393.4	399.6
Methane	12		36.40	77	93.8	-1.544	6.7	565.3	572.0
Methane	13		36.40	-90	-604.2	-4.670	271.7	565.3	837.0
Methane	14		11.96	-120	-625.5	-4.670	422.3	393.4	815.7
Methane	15		11.96	-120	-354.5	-2.901	148.3	393.4	541.7
Within CM1 ($\dot{m}_{21-24}$ = 3.009 kg/s, $\dot{m}_{31-34}$ = 5.207 kg/s, $\dot{m}_{41-42}$ = 56.83 kg/s)									
Methane	11	1.365	18.03	-4	-85.3	-1.774	6.2	457.5	463.7

Methane	12		36.4	70	74.2	-1.600	4.5	565.3	569.8
Methane	13		36.4	-90	-604.2	-4.670	271.7	565.3	837.0
Methane	14		18.03	-110	-616.6	-4.670	367.1	457.5	824.6
Methane	15		18.03	-110	-354.6	-3.065	134.6	457.5	592.1
Within TV1									
($\dot{m}_{21-24} = 2.821$ kg/s, $\dot{m}_{31-34} = 4.881$ kg/s, $\dot{m}_{41-42} = 53.27$ kg/s)									
Methane	11	1.432	18.03	-9	-98.0	-1.821	8.2	457.5	465.7
Methane	12		36.40	40	1.7	-1.821	0.1	565.3	565.4
Methane	13		36.40	-90	-604.2	-4.67	271.7	565.3	837.0
Methane	14		18.03	-110	-604.2	-4.595	356.2	457.5	813.7
Methane	15		18.03	-110	-354.6	-3.065	134.6	457.5	592.1
Within CD2-EV2									
($\dot{m}_{21-24} = 2.754$ kg/s, $\dot{m}_{31-34} = 5.116$ kg/s, $\dot{m}_{41-42} = 55.83$ kg/s)									
Methane	11	1.337	18.03	-2	-79.7	-1.753	5.4	457.5	462.9
Methane	12		36.40	49	23.5	-1.753	0.8	565.3	566.1
Methane	13		35.31	-91	-610.7	-4.704	280.1	560.7	840.8
Methane	14		18.03	-110	-622.0	-4.704	372.0	457.5	829.5
Methane	15		18.03	-110	-354.6	-3.065	134.6	457.5	592.1
Within CM2									
($\dot{m}_{11-15} = 1.365$ kg/s, $\dot{m}_{31-34} = 5.524$ kg/s, $\dot{m}_{41-42} = 60.29$ kg/s)									
Ethylene	21	2.755	2.13	-90	-165.8	-0.9132	48.7	68.6	117.3
Ethylene	22		24.01	83	65.5	-0.707	6.3	279.0	285.3
Ethylene	23		-22.00	24	-440.6	-2.593	80.9	279.0	359.9
Ethylene	24		2.13	-90	-473.5	-2.593	258.5	68.6	327.1
Within TV2									
($\dot{m}_{11-15} = 1.365$ kg/s, $\dot{m}_{31-34} = 5.336$ kg/s, $\dot{m}_{41-42} = 58.24$ kg/s)									
Ethylene	21	3.084	2.13	-90	-165.8	-0.913	48.7	68.6	117.3
Ethylene	22		24.01	46	-3.9	-0.913	0.3	279.0	279.3
Ethylene	23		24.01	-22	-440.6	-2.593	80.9	279.0	359.9
Ethylene	24		2.13	-90	-440.6	-2.414	236.1	68.6	304.7

TABLE 8 (CONTINUATION)

Within CD3-EV3									
($\dot{m}_{11-15} = 1.365$ kg/s, $\dot{m}_{31-34} = 4.867$ kg/s, $\dot{m}_{41-42} = 54.21$ kg/s)									
Ethylene	21	2.731	2.13	-90	-165.8	-0.9132	48.7	68.6	117.3
Ethylene	22		24.01	45.65	-3.888	-0.9132	0.34	279.3	279.3
Ethylene	23		23.29	-23.16	-444.4	-2.608	84.1	276.5	360.6
Ethylene	24		2.13	-90	-476.2	-2.608	260.3	68.6	328.9
Within CM3									
($\dot{m}_{11-15} = 1.365$ kg/s, $\dot{m}_{21-24} = 2.755$ kg/s, $\dot{m}_{41-42} = 53.99$ kg/s)									
Propane	31	4.766	2.27	-22	549.7	2.403	9.8	46.6	56.4
Propane	32		15.00	58	650.7	2.440	10.7	135.4	146.1
Propane	33		15.00	44	319.6	1.398	0.4	135.4	135.8
Propane	34		2.27	-22	297.3	1.398	66.9	46.6	113.5
Within TV3									
($\dot{m}_{11-15} = 1.365$ kg/s, $\dot{m}_{21-24} = 2.755$ kg/s, $\dot{m}_{41-42} = 57.05$ kg/s)									
Propane	31	5.228	2.27	-22	549.7	2.403	9.7	46.6	56.4

Propane	32		15.00	53	638.6	2.403	9.9	135.4	145.3
Propane	33		15.00	44	319.6	1.398	0.4	135.4	135.8
Propane	34		2.27	-22	319.6	1.487	61.9	46.6	108.5
Within CD4									
($\dot{m}_{11-15} = 1.365$ kg/s, $\dot{m}_{21-24} = 2.755$ kg/s, $\dot{m}_{41-42} = 53.27$ kg/s)									
Propane	31	4.975	2.27	-22	549.7	2.403	9.8	46.6	56.4
Propane	32		17.65	61	646.3	2.403	17.1	136.0	153.1
Propane	33		16.62	49	333.3	1.440	0.9	135.8	136.7
Propane	34		2.27	-22	307.8	1.440	64.5	46.6	111.1

TABLE 9
RESULTS OBTAINED FROM THE ADVANCED EXERGETIC ANALYSIS

Component	$\left(\dfrac{\dot{E}_{D,k}}{\dot{E}_{P,k}}\right)^{UN}$	$\dot{E}_{P,k}^{EN}$	$\dot{E}_{D,k}^{EN,AV}$	$\sum_{\substack{r=1 \\ r\neq k}}^{n} \dot{E}_{D,r}^{AV,EX,k}$	$\dot{E}_{D,k}^{AV,\Sigma}$
RHE	0.56	132.20	0.75	5.52	6.27
CM1	0.05	153.30	65.83	86.04	151.87
CD1-EV1	0.05	324.90	27.57	166.49	194.06
TV1	0.27	121.00	0	0.16	0.16
CM2	0.04	596.70	151.91	79.32	231.23
CD2-EV2	0.7	374.40	33.13	86.63	119.76
TV2	0.36	478.10	0	29.56	29.56
CM3	0.05	474.00	33.21	3.37	36.58
CD4	2.07	18.20	28.56	67.35	95.91
TV3	0.44	324.30	0	8.59	8.59
CD3-EV3	0.42	229.50	30.6	25.68	56.28

TABLE 10
RESULTS OBTAINED FROM THE ADVANCED EXERGETIC ANALYSIS (ALL VALUES ARE GIVEN IN KW)

Component	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$			$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{UN}$				$\dot{E}_{D,k}^{AV}$			
							$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$			$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$		
RHE	54.56	21.74	CD1-EV1	13.98	53.81	22.49	53.81	0	CD1-EV1	0	0.75	21.74	CD1-EV1	13.98
			CM1	-3.01					CM1	0			CM1	-3.01
			TV1	6.05					TV1	0			TV1	6.05
			CD2-EV2	-2.62					CD2-EV2	0			CD2-EV2	-2.62
			CM2	0					CM2	0			CM2	0
			TV2	0					TV2	0			TV2	0
			CD3-EV3	0					CD3-EV3	0			CD3-EV3	0
			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	7.34					mexo	0			mexo	7.34
CD1-EV1	44.79	0.35	RHE	0.35	17.35	27.79	17.22	0.13	RHE	0.13	27.57	0.22	RHE	0.22
			CM1	0					CM1	0			CM1	0
			TV1	0					TV1	0			TV1	0
			CD2-EV2	0					CD2-EV2	0			CD2-EV2	0
			CM2	0					CM2	0			CM2	0
			TV2	0					TV2	0			TV2	0
			CD3-EV3	0					CD3-EV3	0			CD3-EV3	0
			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	0					mexo	0			mexo	0
CM1	72.90	43.90	RHE	2.89	12.80	104.0	7.07	5.73	RHE	0.35	65.83	38.17	RHE	2.54
			CD1-EV1	34.80					CD1-EV1	4.88			CD1-EV1	29.92
			TV1	3.28					TV1	0.25			TV1	3.03
			CD2-EV2	-1.35					CD2-EV2	-0.10			CD2-EV2	-1.25
			CM2	0					CM2	0			CM2	0
			TV2	0					TV2	0			TV2	0
			CD3-EV3	0					CD3-EV3	0			CD3-EV3	0

			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	4.28					mexo	0.35			mexo	3.93

TABLE 10 (CONTINUATION)

Com-ponent	$\dot{E}^{EN}_{D,k}$	$\dot{E}^{EX}_{D,k}$			$\dot{E}^{UN}_{D,k}$	$\dot{E}^{AV}_{D,k}$	$\dot{E}^{UN}_{D,k}$				$\dot{E}^{AV}_{D,k}$			
							$\dot{E}^{UN,EN}_{D,k}$	$\dot{E}^{UN,EX}_{D,k}$			$\dot{E}^{AV,EN}_{D,k}$	$\dot{E}^{AV,EX}_{D,k}$		
TV1	33.41	23.43	RHE	0.26	48.87	7.97	33.41	15.46	RHE	-0.40	0	7.97	RHE	0.66
			CD1-EV1	28.54					CD1-EV1	16.37			CD1-EV1	12.17
			CM1	0					CM1	0			CM1	0
			CD2-EV2	-3.66					CD2-EV2	-4.28			CD2-EV2	0.62
			CM2	0					CM2	0			CM2	0
			TV2	0					TV2	0			TV2	0
			CD3-EV3	0					CD3-EV3	0			CD3-EV3	0
			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	-1.71					mexo	3.77			mexo	-5.48
CD2-EV2	293.00	206.70	RHE	2.20	275.97	223.73	259.87	16.10	RHE	2.01	33.13	190.60	RHE	0.19
			CD1-EV1	80.90					CD1-EV1	-5.76			CD1-EV1	86.66
			CM1	66.40					CM1	-0.07			CM1	66.47
			TV1	-2.80					TV1	11.52			TV1	-14.32
			CM2	0					CM2	0			CM2	0
			TV2	0					TV2	0			TV2	0
			CD3-EV3	0					CD3-EV3	0			CD3-EV3	0
			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	60.00					mexo	8.40			mexo	51.60
CM2	174.70	133.0	RHE	1.30	42.86	264.84	22.79	20.07	RHE	0.18	151.91	112.93	RHE	1.12
			CD1-EV1	16.90					CD1-EV1	2.22			CD1-EV1	14.68
			CM1	16.10					CM1	2.11			CM1	13.99
			TV1	4.20					TV1	0.55			TV1	3.65

			CD2-EV2	31.10					CD2-EV2	5.88			CD2-EV2	25.22
			TV2	20.90					TV2	2.73			TV2	18.17
			CD3-EV3	-1.50					CD3-EV3	-0.19			CD3-EV3	-1.31
			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	44.00					mexo	6.59			mexo	37.41

TABLE 10 (CONTINUATION)

Com-ponent	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$			$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{UN}$				$\dot{E}_{D,k}^{AV}$			
							$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$			$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$		
TV2	170.40	128.30	RHE	1.30	269.21	29.49	170.40	98.81	RHE	1.76	0	29.49	RHE	-0.46
			CD1-EV1	16.60					CD1-EV1	17.06			CD1-EV1	-0.46
			CM1	15.80					CM1	16.27			CM1	-0.47
			TV1	4.10					TV1	4.58			TV1	-0.48
			CD2-EV2	68.40					CD2-EV2	38.36			CD2-EV2	30.04
			CM2	0					CM2	0			CM2	0
			CD3-EV3	-8.20					CD3-EV3	-2.39			CD3-EV3	-5.81
			CM3	0					CM3	0			CM3	0
			TV3	0					TV3	0			TV3	0
			CD4	0					CD4	0			CD4	0
			mexo	30.30					mexo	23.17			mexo	7.13
CD3-EV3	111.50	250.80	RHE	0.90	121.96	240.34	80.90	41.06	RHE	0.63	30.6	209.74	RHE	0.27
			CD1-EV1	10.80					CD1-EV1	7.86			CD1-EV1	2.94
			CM1	10.30					CM1	7.51			CM1	2.79
			TV1	2.70					TV1	1.94			TV1	0.76
			CD2-EV2	29.50					CD2-EV2	0			CD2-EV2	29.50
			CM2	68.90					CM2	0			CM2	68.90
			TV2	12.70					TV2	9.23			TV2	3.47
			CM3	0					CM3	0			CM3	0
			TV3	2.70					TV3	1.94			TV3	0.76
			CD4	0					CD4	0			CD4	0

			mexo	112.3					mexo	11.95			mexo	100.35
CM3	54.11	106.09	RHE	0.42	64.64	95.56	20.90	43.74	RHE	0.16	33.21	62.35	RHE	0.26
			CD1-EV1	5.26					CD1-EV1	2.03			CD1-EV1	3.23
			CM1	5.01					CM1	1.94			CM1	3.07
			TV1	1.31					TV1	0.51			TV1	0.80
			CD2-EV2	3.98					CD2-EV2	1.54			CD2-EV2	2.44
			CM2	8.61					CM2	3.33			CM2	5.28
			TV2	6.48					TV2	2.51			TV2	3.97
			CD3-EV3	11.87					CD3-EV3	5.24			CD3-EV3	6.63
			TV3	6.66					TV3	2.21			TV3	4.45
			CD4	5.87					CD4	2.70			CD4	3.17
			mexo	50.62					mexo	21.57			mexo	29.05

TABLE 10 (CONTINUATION)

Component	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$			$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{UN}$				$\dot{E}_{D,k}^{AV}$			
							$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$			$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$		
TV3	142.80	324.90	RHE	1.10	343.16	124.54	142.80	200.36	RHE	0.60	0	124.54	RHE	0.50
			CD1-EV1	13.90					CD1-EV1	13.31			CD1-EV1	0.59
			CM1	13.20					CM1	12.65			CM1	0.55
			TV1	0					TV1	0			TV1	0
			CD2-EV2	10.50					CD2-EV2	9.92			CD2-EV2	0.58
			CM2	22.70					CM2	22.11			CM2	0.59
			TV2	17.10					TV2	16.57			TV2	0.53
			CD3-EV3	60.50					CD3-EV3	36.54			CD3-EV3	23.96
			CM3	0					CM3	0			CM3	0
			CD4	31.00					CD4	0.95			CD4	30.05
			mexo	154.90					mexo	87.71			mexo	67.19
CD4	66.22	104.18	RHE	0.50	97.59	72.81	37.66	59.93	RHE	0.28	28.56	44.25	RHE	0.22
			CD1-EV1	6.42					CD1-EV1	3.64			CD1-EV1	2.78
			CM1	6.12					CM1	3.47			CM1	2.65
			TV1	1.58					TV1	0.91			TV1	0.67
			CD2-EV2	4.85					CD2-EV2	2.75			CD2-EV2	2.10
			CM2	10.52					CM2	5.97			CM2	4.55

			TV2	7.93	TV2	4.51	TV2	3.42
			CD3-EV3	3.80	CD3-EV3	1.59	CD3-EV3	2.21
			CM3	4.94	CM3	1.59	CM3	3.35
			TV3	7.80	TV3	4.42	TV3	3.38
			mexo	49.72	mexo	30.80	mexo	18.92

vane) compressor instead of the piston compressor assumed here. In addition, a screw type refrigeration compressor can be considered only for CM1 because of the limitations associated with its operating conditions. The components CD1-EV1 and CD2-EV2 can be improved by decreasing the temperature difference in these heat exchangers. The assumed value for the minimum temperature difference of 10K for all three CD-EVs is relatively high and easily can be decreased down to 6K (without selecting a different type of heat exchanger), or even down to 4 … 2K. The value ΔT_{min}=2 K corresponds to standard operation conditions for plate heat exchangers.

5. CONCLUSIONS

We conclude that a conventional exergetic analysis provides useful information, but an advanced exergetic analysis makes this information more precise and useful and supplies additional information that cannot be provided by any other analysis.

The avoidable exergy destruction identifies the potential for improving each system component. The values of the sum of the avoidable exergy destruction is a new and very important variable in the advanced exergetic analysis because this value summarizes all information obtained from the advanced exergetic analysis and shows the relative importance of improving single components and the structure of the overall system.

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7. NOMENCLATURE

E	exergy [J]
e	specific exergy [J/kg]
k	k th component [-]
m	mass [kg]
n	number of components [-]
p	pressure [Pa]
r	r th component (different from the k th component being considered) [-]
T	temperature [K]
y	exergy destruction ratio [-]

Greek symbols

ε	exergetic efficiency [%]
η	isentropic efficiency [%]

Subscripts

D	refers to exergy destruction
F	fuel
P	product
tot	refers to the total system

Superscripts

●	time rate
AV	avoidable
EN	endogenous
EX	exogenous
M	mechanical exergy
PH	physical exergy
T	thermal exergy
UN	unavoidable

Abbreviations

CD	condenser
CD-EV	condenser-evaporator
CM	compressor
RHE	regeneration heat exchanger
TV	throttling valve

8. REFERENCES

[1] EIA – Energy Information Administration of U.S., http://www.energy.ca.gov/lng/international.html.

[2] "Liquefied Natural Gas: Current Expansion and Perspectives", 19-th Informatory Note on Refrigerating Technologies. *International Institute of Refrigeration*, Paris, France, www.iifiir.org, 2006.

[3] "Refrigeration. ASHRAE Handbook", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2006.

[4] M.N. Bin Omar, "Efficiency Improvement of a General System for the Production of Malaysia Liquefied Natural Gas (MLNG)", Ms. Thesis, Technische Universität Berlin, 2008.

[5] T. Morosuk, N.M. Bin Omar, G. Tsatsaronis, R. Naw R. "Advanced exergetic analysis of a refrigeration system for liquefaction of natural gas", *Proceedings of the 23-rd International Conference on Efficiency, Cost, Optimization Simulation and Environmental Impact of Energy Systems*, June 13-17, Lausanne, Swiss, CD-ROM, 2010, 10 pages.

[6] G. Tsatsaronis, “Definitions and nomenclature in exergy analysis and exergoeconomics”. *Energy – The International Journal*, Vol. 32**,** pp. 249-253, 2007.

[7] T. Morosuk, G. Tsatsaronis, “Graphical models for splitting physical exergy”. In: Kjelstrup S, Hustad JE, Gundersen T, Rosjorde A, Tsatsaronis G, editors. *Shaping our future energy systems*. Vol. 1, pp. 377–384, 2005.

[8] A. Bejan, G. Tsatsaronis, M. Moran, *Thermal Design and Optimization*, John Wiley & Sons, New York, 1996.

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

[10] G. Tsatsaronis, “Combination of Exergetic and Economic Analysis in Energy-Conversion Processes”. In: *Energy Economics and Management in Industry*, Proceedings of the European Congress, Algarve, Portugal, April 2-5, 1984, England, Oxford: Pergamon Press, Vol. 1, pp. 151-157, 1984.

[11] A. Lazzaretto, G. Tsatsaronis, “SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems”, *Energy – The International J*ournal, Vol. 31, pp. 1257-1289, 2006.

[12] G. Tsatsaronis, T. Morosuk, “A general exergy-based method for combining a cost analysis with an environmental impact analysis. Part I”, Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Boston, Massachusetts, USA, 2008, files IMECE2008-67218.

[13] G. Tsatsaronis, T. Morosuk, “A general exergy-based method for combining a cost analysis with an environmental impact analysis. Part II”, Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Boston, Massachusetts, USA, 2008, files IMECE2008-67219.

[14] T. Morosuk, G. Tsatsaronis, “New approach to the exergy analysis of absorption refrigeration machines”, *Energy – The International Journal*, Vol. 33, pp. 890-907, 2008.

[15] T. Morosuk, G. Tsatsaronis, “Advanced Exergetic Evaluation of Refrigeration Machines Using Different Working Fluids”, *Energy – The International Journal*, Vol. 34, pp. 2248-2258, 2009.

[16] T. Morosuk, G. Tsatsaronis, “Advanced Exergy Analysis for Chemically Reacting Systems – Application to a Simple Open Gas-Turbine System”, *International Journal of Thermodynamics*, Vol. 12, No. 3, pp. 105-111, 2009.

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