Advanced exergy analysis applied to the process of regasification of LNG integrated into an air separation process

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Abstract:

Natural gas is to one of the most important sources of energy. We expect the demand for natural gas to increase in the future. The liquefied natural gas (LNG) market rises currently exponentially; many countries entered this market recently. Using an efficient regasification process for LNG is now more important than in the past.
At present, only regasification of LNG via direct or indirect heating is used for industrial applications. Regasification of LNG can be combined with generation of electricity. Another possibility is the integration of the regasification in processes requiring low temperatures. A new option dealing with the integration of regasification of LNG to a cryogenic process of air separation has recently been developed at TU Berlin.
This paper evaluates two options related to the integration of the regasification of LNG into an air separation system. Conventional and advanced exergy analyses are used in the evaluation.

Keywords:

LNG, regasification, air separation, advanced exergy analysis.

1 Introduction

The increasing demand for energy sources all over the world leads to a growing demand of natural gas. It is expected, that natural gas will provide approximately 30 % [1] of the primary energy supply in the world by 2030. In connection with natural gas also the global market for liquefied natural gas (LNG) is growing rapidly. For example, the Asian LNG market has a large effect with 75 % of the global LNG demand [1]. The use of LNG has several advantages compared with gaseous natural gas, including lower transportation costs in case of a distance longer than 2000 km [2] and flexibility to receive LNG from different countries. A disadvantage is the large cost for the complete LNG chain, which consists of liquefaction, transportation, storage and regasification. But with improving technologies and with the increasing number of LNG plants during the last years, the total cost for the LNG chain has been decreasing [3]. At the end of 2013 there were 86 liquefaction plants in operation in 17 exporting countries [4]. Also, the number of LNG import terminals and the number of countries with LNG receiving terminals increased during the last years (104 import terminals in 29 importing countries [4]).
In the import terminal different types of regasification processes have been used [5-6]. The regasification is mostly accomplished via direct or indirect heating. In these cases the source of thermal energy is seawater, air or the heat from combustion gases generated with natural gas. Just a few import terminals are using process integration for the regasification of LNG. These processes are reported in detail in [6].
This paper deals with the integration of regasification of LNG into an air separation process. An attempt to combine the regasification of LNG with a cryogenic process has been reported in [7-8]. Here a revised version of this concept and a new developed option of integration are discussed. The

systems are evaluated from the exergetic point of view. Also, the results from an advanced exergy analysis are reported for both systems.

2 Process description

The two processes (Design 1 and Design 2) consist of four main blocks: (1) air purification and compression block, (2) liquefaction of air in the main heat exchangers (MHE1 and MHE2), (3) column block and (4) nitrogen liquefaction block.

The heat exchangers to liquify the air and the column block are embedded in a component, which is called "cold box". The nitrogen liquefaction block could have different designs.

The column block consists of a double-column system. For the simulation of the cryogenic columns, important design parameters such as the reflux ratios and the number of stages [9] are considered. At the top of the high-pressure column almost pure nitrogen (gaseous) is leaving. The bottom product which is an oxygen rich mixture is throttled and enters the low-pressure column. Regarding this column the bottom products are liquid and gaseous oxygen and the top product is gaseous nitrogen. A by-product of the low pressure column is a stream, which consists of non-condensable gases (purge gas). The column block is identical in both systems and was simplified regarding to the single air separation plant in [7]. Here we assumed that the air is only separated into nitrogen and oxygen.

2.1 Design 1

Figure 1 shows the conceptual flowsheet of Design 1. The air at environmental conditions is compressed to around 6 bar [10] within a two stage compression process. Before air enters the first compressor dust particles are removed. Between both compressors the air is cooled down and the humidity of the air is removed in the subsequent flash separator. In real air separation plants the water and also the CO_2 content are removed within an adsorber bed system. This system consists of two separate beds which are working alternatively. If the air is cleaned in one bed, the second bed is cleaned by the purge gas stream. After some minutes the streams are switched, and the beds start working vice versa [11]. The cleaned air enters the main heat exchanger (MHE1 and MHE2). The air is cooled down in the MHE1 to approximately $-130\,°C$ and in the MHE2 to approximately $-170\,°C$. Then the air enters the column block. The purge gas and oxygen streams which are leaving the column block are heated up in the main heat exchanger by cooling the air down to the liquefaction temperature. Both nitrogen streams, which are leaving the column block (top products of the high- and low-pressure columns), are fed to the nitrogen liquefaction block. In Design 1 this block consists of three compressors (NC1 through NC3), one interstage cooler, one expander, two heat exchangers (HE1 and HE2), a throttle valve and some mixing and splitting devices. One of the two mentioned nitrogen streams is liquefied in the nitrogen liquefaction block. First, this stream is heated up in both heat exchangers and is then compressed to 46 bar [9] in a three-stage compression process with interstage cooling. Afterwards it is cooled down in HE1 and is split into two streams. One part of the nitrogen is expanded in a turbine which supplies the necessary work to the third nitrogen compressor. The second part is further cooled down within HE2 and leaves it in liquid form. Afterwards this stream is split into two parts, one part is leaving the system as a liquid product of nitrogen and the second part is throttled to the pressure at the top of the low-pressure column and is returned there. The second nitrogen stream, which leaves the column block is heated up stepwise in three different heat exchangers. This nitrogen stream enters first the MHE2, then the HE2 in the nitrogen liquefaction block and finally the MHE1.

The LNG which is delivered by a ship with a temperature of $-163\,°C$ and a pressure of 1.3 bar is brought into the system by a pump (P). In the MHE the LNG is heated up and removed it in gaseous state.

The product streams of oxygen and nitrogen leaving the MHE are compressed here to 20 bar. This value depends however on the requirements of the consumer. In the two following heat exchangers (HE3 and HE4) both streams are needed to heat up the purge gas to $170\,°C$ [9] and the LNG stream to

the environmental temperature. The purge gas is heated up to a temperature of 170 °C to desorb the impurities in the adsorber beds.

2.2 Design 2

Design 2 is a new developed option to integrate LNG into an air separation process (Figure 2). A general difference compared to Design 1 is the integration of LNG in all heat exchangers. At the beginning, the air at environmental conditions and free of dust particles is compressed in three compressors (with intermediate cooling) to around 6 bar [10]. In both interstage coolers heat is transferred from the air to the LNG. After the first interstage cooler a flash separator removes the humidity of the air. This has a positive effect on the following compressors. The air enters both of them with a lower temperature which decreases the required work. In the cooling of the air with LNG it is considered that the temperature of the air at the outlet of the compressor is approximately 5 °C higher than the environmental temperature to avoid condensation of water at the housing of the compressor. After the compression process the air enters the main heat exchanger and is cooled down in two steps to approximately −153 °C. By an additional heat exchanger after the MHE the air is cooled down to the required liquefaction temperature of −173 °C and enters the column block. Comparing the main heat exchanger in both options it is obvious that the arrangement of the streams differs. This is partially caused by the LNG stream.

LNG is also brought into the system with a pump (P) but then it is split into two parts. One part is heated up in the additional heat exchanger (HE1) before it enters the MHE1. The second part flows directly to the nitrogen liquefaction block. Finally both streams are mixed and further heated up in the interstage coolers (IC1 and IC1A). One of the main differences between the two options is the structure of the nitrogen liquefaction block. In this system the liquefaction block consists only of two nitrogen compressors (NC1 and NC2) and one heat exchanger (HE2). The nitrogen stream leaving the column block at the top of the high-pressure column is fed to the liquefaction block, where it is heated up in the HE2 and is then compressed to 46 bar [9]. Afterwards it is cooled down and liquefied in the HE2. This stream is split: while one part is leaving the system as liquid product of nitrogen, the second stream is throttled to the pressure at the top of the low pressure column and enters it. Additionally also one part of the LNG stream as well as the nitrogen stream which is the top product of the low-pressure column enters the nitrogen liquefaction block. Both are heated up in the HE2 by cooling the already mentioned second nitrogen stream to liquefaction temperature.

The streams leaving the MHE1 (purge gas, oxygen, nitrogen and LNG) are the same as in Design 1. Also in this option the nitrogen and oxygen streams are compressed to 20 bar. Afterwards the purge gas is heated (HE3) with the oxygen stream to the required temperature of 170 °C [9] to desorb the impurities in the adsorber bed systems. Finally the LNG stream is heated up (HE4) to the environmental temperature with the oxygen stream, nitrogen stream and purge gas stream.

3 Simulation and energy analysis

The simulation was carried out using ASPEN PLUS [12]. For the turbomachines (compressors, expanders and pumps) we assumed the following:

- The isentropic efficiencies of the compressors and the expanders are 84 %
- The isentropic efficiency of the pump is 70 %
- The mechanical efficiency of all turbo-machines is 99 %.

Figure 3 shows the varying power consumption for the turbo-machines. In this figure also the amount of electrical power for the Base Case is shown. The Base Case consists of the single air separation process alone. The flowsheet of this process and the results of this simulation are taken from [7].

It is obvious that the total amount of electricity needed decreases from Base Case to Design 1 and finally to Design 2. Even if the expanders are taken into consideration in Base Case and Design 1,
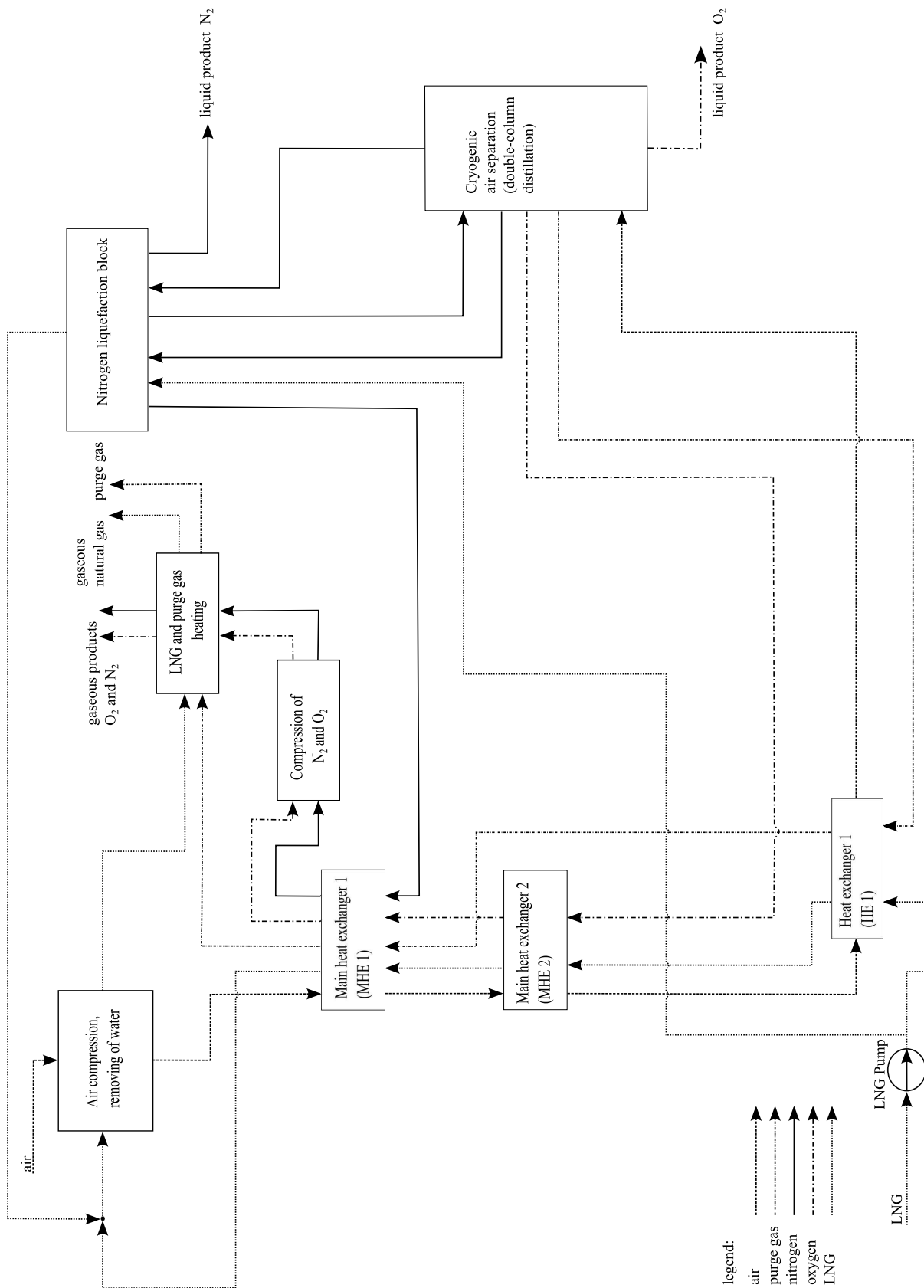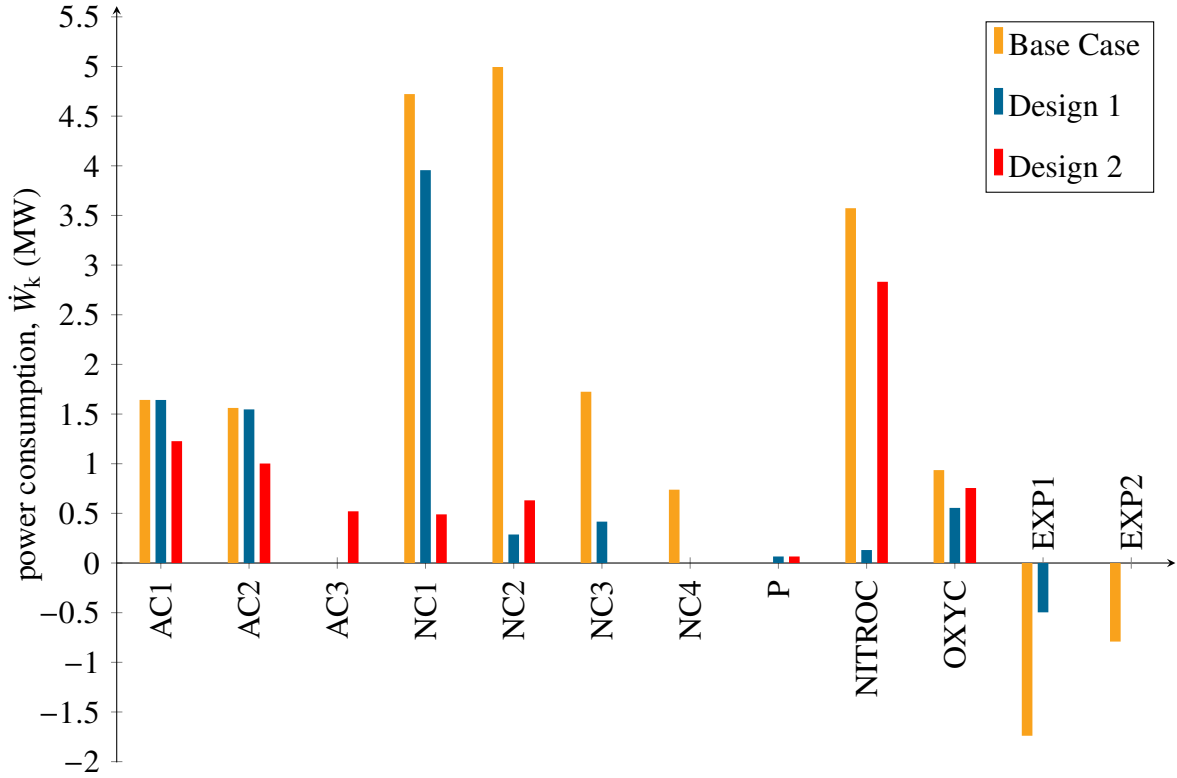
liquid product N₂

liquid product O₂

Cryogenic
air separation
(double-column
distillation)

Nitrogen liquefaction block

gaseous
natural gas   purge gas

LNG and purge gas
heating

gaseous products
O₂ and N₂

Compression of
N₂ and O₂

Main heat exchanger 1
(MHE 1)

Main heat exchanger 2
(MHE 2)

Air compression,
removing of water

air

LNG Pump

LNG

legend:
air
purge gas
nitrogen
oxygen
LNG

Fig. 1. Conceptual schematic of Design 1

Fig. 2. Conceptual schematic of Design 2

Fig. 3. Comparison of the power consumption for the turbo-machines

the total amount of power consumption is $\dot{W}_{net,BC} = 17.4\,\text{MW}$ and $\dot{W}_{net,D1} = 8.1\,\text{MW}$ respectively. In comparison to this, Design 2 has a power consumption of $\dot{W}_{net,D2} = 7.5\,\text{MW}$.

4 Exergy Analysis

For conducting an exergy analysis average European environmental conditions are assumed: $T_0 = 15\,°\text{C}$ and $p_0 = 1.013$ bar. For each component the exergy of fuel and of product are defined according to [13] and the exergy destruction for the overall system (1) and for the components (2) is calculated as:

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot} \tag{1}$$

and

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \tag{2}$$

The concept of dissipative components was applied to interstage cooler 1 together with the flash separator in the air purification and compression block (Design 1 and Design 2) and mixing devices (Design 1 and Design 2). In some components the process occurs by crossing the temperature of the environment. In this case it is necessary to split the physical exergy of each stream into its thermal and mechanical part [14]. Some results of the exergy analysis are shown in Table 1 and Fig. 4.
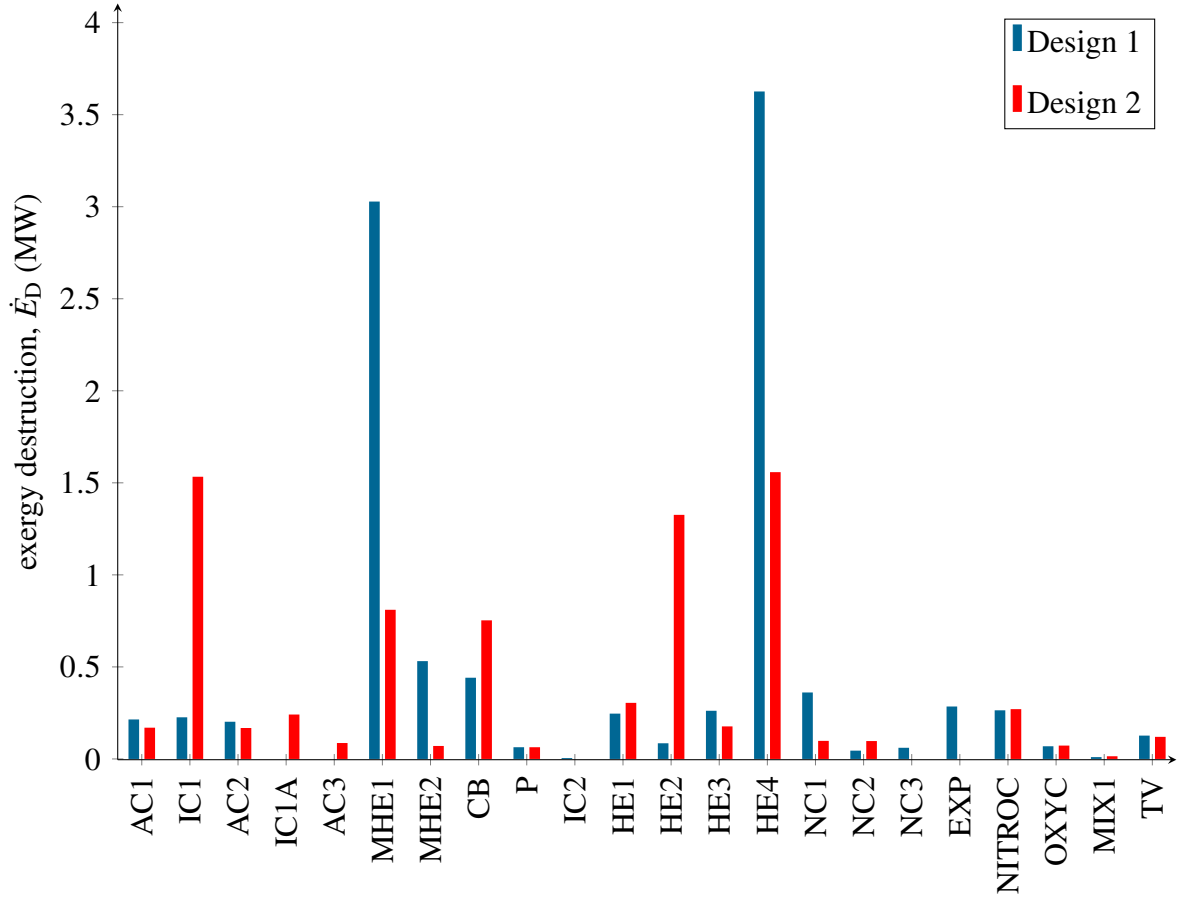
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Fig. 4. Exergy destruction of the components in Design 1 and Design 2

Table 1. Results obtained from the exergy analysis of the overall system (Design 1 and Design 2)

	$\dot{E}_{F,tot}$, MW	$\dot{E}_{P,tot}$, MW	$\dot{E}_{D,tot}$, MW	$\dot{E}_{L,tot}$, MW	ε_{tot}, %
Design 1	20.31	9.87	10.39	0.05	49
Design 2	17.78	9.77	7.93	0.08	55

5 Advanced exergy analysis

In addition to a conventional exergy analysis, an advanced exergy analysis [15] was applied to both Designs. The exergy destruction within each system component is split into unavoidable and avoidable and exogenous and endogenous parts:

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{UN} + \dot{E}_{D,k}^{AV} \tag{3}$$

and

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EX} + \dot{E}_{D,k}^{EN}. \tag{4}$$

The unavoidable exergy destruction represents the amount of exergy destruction which could not be further reduced. For the compressors it was assumed that the technological limitations correspond to a value of the isentropic efficiency of 90 %. For the heat exchangers the parameter that identifies the technological limitations is the minimal temperature difference in each heat exchanger. This minimum

value was assumed to be 0.5 K.

The endogenous exergy destruction is the part of the total exergy destruction which occurs in a component when this component operates with the same performance as in the real system and all other components behave like ideal components. Thus, the exogenous exergy destruction is the part which occurs within this component due to irreversibilities within the remaining components. Finally the unavoidable, avoidable, endogenous and exogenous exergy destruction are combined in the resulting variables $\dot{E}_{D,k}^{EN,UN}$, $\dot{E}_{D,k}^{EX,UN}$, $\dot{E}_{D,k}^{EN,AV}$ and $\dot{E}_{D,k}^{EX,AV}$.

The endogenous unavoidable part and the exogenous unavoidable part of the exergy destruction could not be reduced due to technological limitations within the component itself or the remaining components, respectively. In contrast, the endogenous avoidable and exogenous avoidable part of the exergy destruction could be further reduced by improving the component itself, through structural changes and/or by improving the exergetic efficiency of the remaining components. The results of the advanced exergy analysis are shown in Figs. 5 and 6. Dissipative components and the column block were not evaluated in the advanced exergy analysis.
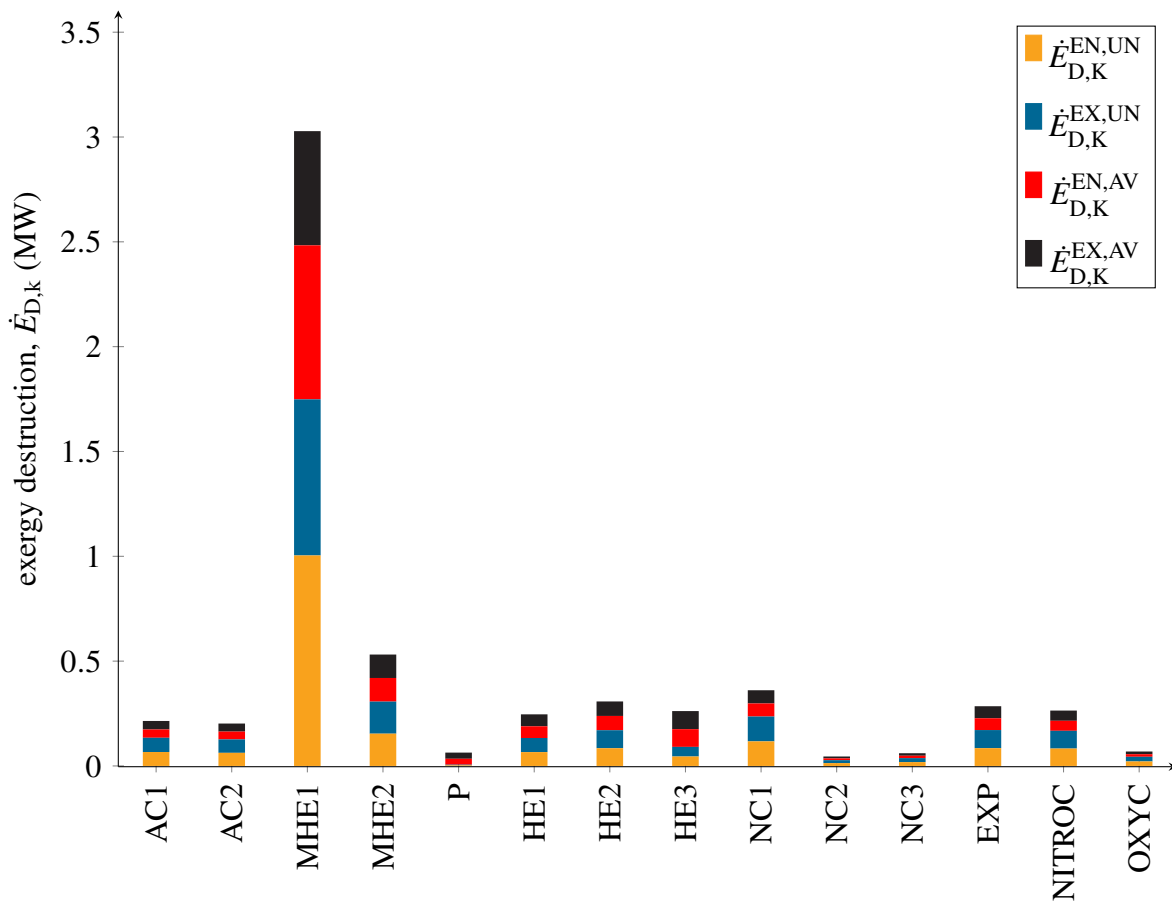

Fig. 5. Results obtained from the advanced exergy analysis of Design 1

6 Discussion

As it is shown in Fig. 3, the power consumption for the air compressors is the same for the Base Case and Design 1, whereas for Design 2 it is lower. This is due to the fact that water at environmental temperature is used for the interstage cooling process in Base Case and Design 1. In Design 2, the LNG stream is used in the interstage coolers with a lower temperature, which results in lower power consumption. The major difference refers to the power within the nitrogen liquefaction associated with the first nitrogen compressor. The pressure ratio within this compressor has the highest value in
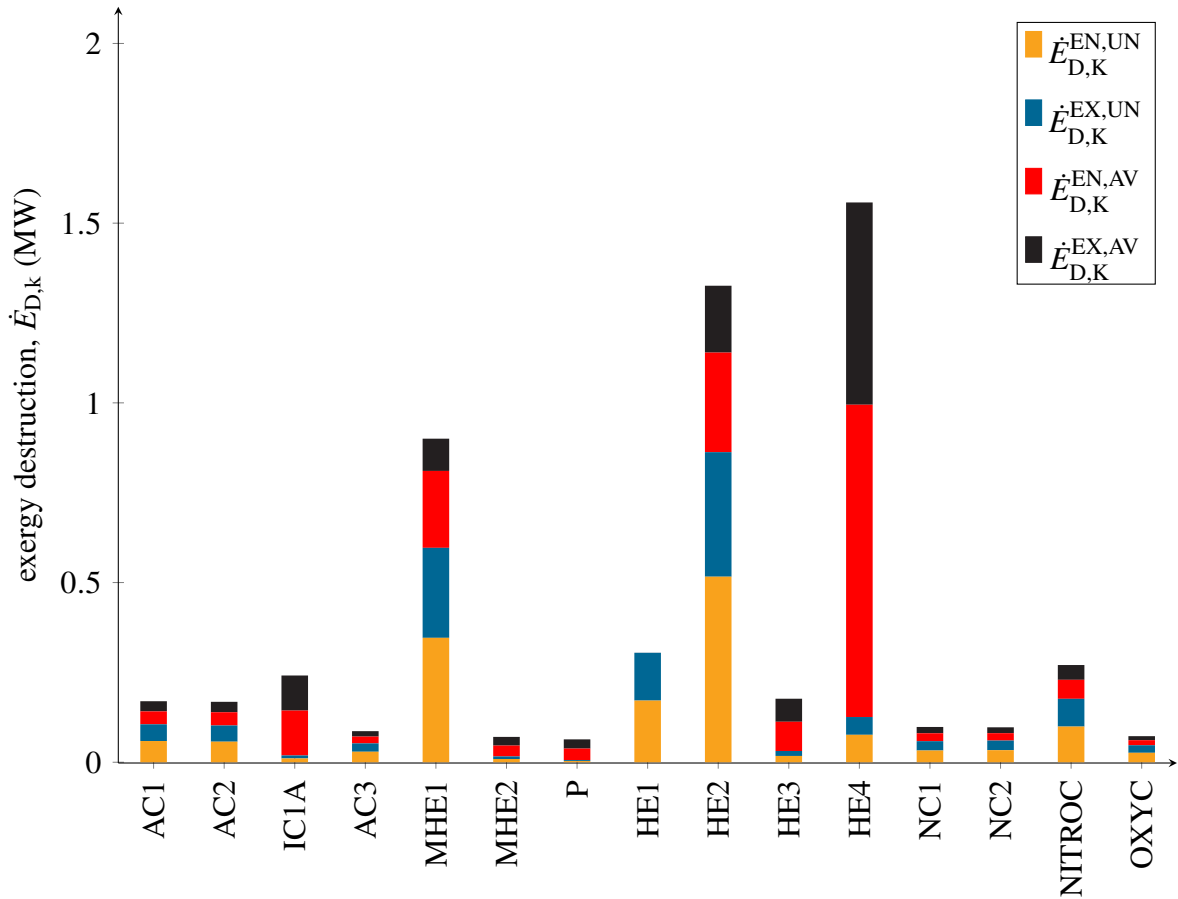
Fig. 6. Results obtained from the advanced exergy analysis of Design 2

Design 1. However, there are two more parameters which influence the total power consumption: (a) the inlet temperature, and (b) the mass flow rate of the stream entering the first nitrogen compressor. In Design 2 the inlet temperature is very low which leads to a lower specific power consumption and, finally, leads to a decrease in the mass flow rate. The power consumptions for the oxygen and nitrogen compressors (installed after the main heat exchanger) are affected by the operation conditions of the previous components, therefore the power consumption of these compressors is lower for Design 1 than for the Base Case and Design 2.

From the exergetic point of view the overall efficiency increases from Design 1 to Design 2, which is caused by the lower exergy destruction, while the exergy of product remains almost constant (Table 1). The major differences in the value of the exergy destruction (Fig. 4) occur in MHE1, HE2 and HE4. Note that for Design 2, the air entering the main heat exchanger has a lower temperature compared with Design 1, which leads to a lower temperature difference in the heat exchanger and, finally, to a lower exergy destruction. The lower temperature of the incoming air is the consequence of the three stage compression and interstage cooling in Design 2. When comparing the results for HE2, the exergy destruction increases strongly in Design 2. This is caused by the modified structure of the nitrogen liquefaction block. As already mentioned, the liquefaction block of Design 2 consists only of two compressors and one heat exchanger (HE2). In HE2, the compressed nitrogen is cooled down to the required temperature that is necessary for the low pressure column. Regarding Design 1, two heat exchangers are used to cool down the compressed nitrogen stream to the same temperature. Finally, the temperature difference increases if only one heat exchanger is used as in Design 2. The exergy destruction within HE 4 decreased by a factor of two from Design 1 to Design 2. In Design 1 an additional stream from the nitrogen liquefaction block is necessary to heat up the LNG stream to the environmental temperature.

Finally, the results from the advanced exergy analysis are discussed based on the numbers shown in Figs. 5 and 6. The avoidable part of the exergy destruction within MHE1 in Design 1 is approximately 50 % of the total value, while the endogenous avoidable value is slightly higher than the exogenous avoidable. This means that MHE1 can be improved by changing the operation conditions within this component as well as through improvement of other components. For the remaining components of Design 1, the value of the unavoidable exergy destruction is higher than the avoidable one, which means that the potential for improvement for the overall system by improving the remaining components, is not very large.

In Design 2 (Fig. 6), the three heat exchangers (MHE1, HE2 and HE4) should be evaluated closer. The unavoidable part of the exergy destruction within MHE1 and HE2 is lower that the avoidable one, however, the avoidable endogenous part is higher than the exogenous avoidable one. This means that we should focus on the operation conditions within these components.

MHE1 in Design 1 is the most important component from the exergetic point of view. In Design 2 this component has much lower exergy destruction with a different distribution between unavoidable/avoidable and endogenous/exogenous parts of the exergy destruction.

The exergy destruction within all compressors decreases significantly from Design 1 to Design 2 which indicates that, in general, there is no need to pay additional attention to the design of the compressors, because the structural improvement of the overall system has a higher priority.

7 Conclusion

In this paper two options for integration of the regasification of LNG into an air separation system have been evaluated. Energetic analysis shows, that the total power consumption decreases from Design 1 to Design 2. The conventional and advanced exergetic analyses demonstrate the total value of the exergy destruction within each component of both designs and the splitting of the exergy destruction into unavoidable/avoidable and endogenous/exogenous parts. MHE1 in Design 1 is the most important component. The exergy destruction in it can be reduced by improving this component (decreasing the endogenous part of the exergy destruction) and/or the remaining components (decreasing the exogenous part of the exergy destruction).

Within Design 2 the irreversibilities within the three heat exchangers MHE1, HE2 and HE4 are significant. The potential for improving these heat exchangers is relative high. Current work deals with the structural improvement of these systems. At present, safety problems have not been considered. We expect that considering these problems will affect the structure of the system.

Acknowledgments

Nomenclature

$\dot{E}$	exergy rate	kW
p	pressure	bar
T	temperature	°C
$\dot{W}$	power	kW

Greek symbols:

ε	exergetic efficiency	*%*

Subscripts and superscripts:

0	enivronmental conditions
AV	avoidable
BC	Base Case
D	destruction
D1	Design 1
D2	Design 2
EN	endogenous
EX	exogenous
F	fuel
k	k-th component
L	loss
net	netto
P	product
UN	unavoidable
tot	total

Abbreviations:

AC	air compressor
CB	column block
EXP	expander
LNG	liquefied natural gas
HE	heat exchanger
MHE	main heat exchanger
IC	interstage cooler
NC	nitrogen compressor (in the liquefaction block)
NITROC	nitrogen compressor
OXYC	oxygen compressor
P	pump
TV	throttling valve

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