Thermo-Ecological analysis of Recovery of LNG cryogenic exergy by electricity production

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Abstract

Natural gas is a fossil fuel with the highest growth dynamics in the global energy mix. The transport of gas in liquefied form (LNG) is an alternative to traditional pipelines. The gas liquefaction process is very energy intensive. Part of the energy used in this process is stored in LNG as cryogenic exergy. In a conventional regasification process, this exergy is lost by release into seawater or another factor serving as an external heat source. There are many concepts for the use of LNG cryogenic exergy. Among possible applications to use LNG for the production of electricity are: using it as the lower heat source in thermodynamic cycles or directly as a working fluid.

As part of this work, two technological systems have been modeled: simple CCGT power plant and CCGT plant integrated with LNG regasification. Both cycles were subjected to a deep analysis by the means of exergy and thermoeconomic analysis. Special algorithm (so-called matrix method) for exergy cost calculations and diagnosis has been tested. The method proved to be a perfect tool for analyzing even complex cycles. However, it was found that the algorithm cannot cope with exergy diagnosis for systems where fluid temperature is crossing the ambient temperature as it requires unambiguous and binary exergy sinks and sources (fuel and product) definition. Suggestions were included in the work to improve the method to work for any system.

Key words: LNG, exergy, CCGT, regasification, energy recovery, thermoeconomic analysis

1. Introduction

1.1. Motivation

Modern trends show a dynamic growth of natural gas share in world energy mix. Natural gas used to be transported in gaseous state by pipelines or gas tankers but within last two decades rapid growth of an alternative way of transportation has emerged – LNG (Liquified Natural Gas). LNG demand is expected to continue growing.

Natural gas and LNG consequently are being chosen as an energy source thanks to their easy and cost-effective technologies for transforming it into heat or work as well as balanced environmental impact. However, there is no technology which is free of imperfections and energy losses, even though many engineers and scientists have spent their lives improving it. It implies a need for constant development.

Main focus in the dissertation is put on thermoeconomic analysis and employing so-called matrix method for this. The matrix method is a not widely known tool, however it offers opportunities for analyzing very complex (multi-component) systems in time shorter than standard analysis. The motivation for the thesis was to promote the method and to test how it copes with atypical cycle – Combined Cycle Gas Turbine integrated with LNG regasification.

Additionally, the idea for the diploma was to compare two cycles: one classic CCGT (Combined Cycle Gas Turbine) and second CCGT integrated with LNG regasification by the means of their thermodynamic performance.

1.2. Objectives

The aim of this work is to conduct a thermoeconomic analysis of an exemplary CCGT plant and subsequently analysis of a selected CCGT plant integrated with LNG regasification. The calculation algorithm for this diagnosis was based on a matrix method that allows an easy and transparent way to analyze even very complex systems. This method will be previously presented and explained what will allow to clearly understand the issues discussed. As part of the calculations, the following software was used: Thermoflex 26 [1], CoolProp [2], REFPROP [3], Microsoft Excel.

2. Liquified Natural Gas

2.1. LNG as a way of natural gas transportation

The condensation of methane allows to increase the energy density to about 21 GJ per cubic meter. After delivery of LNG to the destination, it is regasified to the gas form. The advantage of transporting natural gas in the form of LNG is its flexibility. The natural gas supplier is not rigidly connected to the customer through the pipeline. Figure 1 presents cost comparison of natural gas transportation by pipelines and LNG. Liquified natural gas becomes more profitable as a way of transportation for long-distance transport [4].

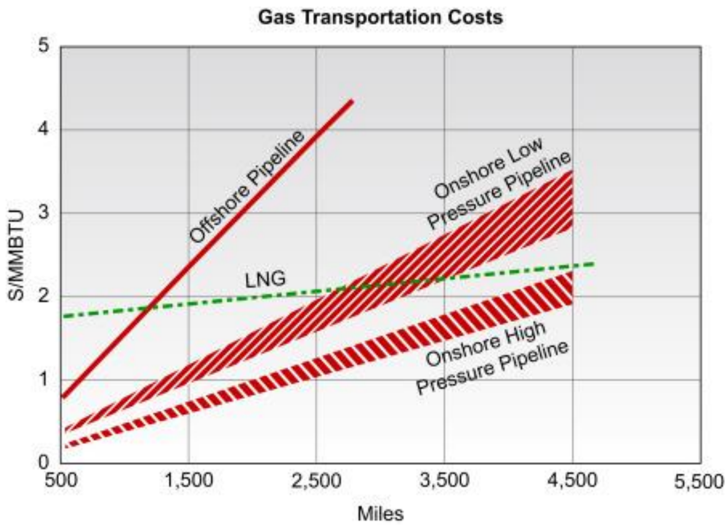

Figure 1 Comparison of the cost of transporting gas via pipeline and LNG; for 1 trillion cubic feet/year and including regasification costs [4]

The LNG production and supply chain are shown schematically in Figure 2. It consists of four main stages: natural gas extraction, purification and liquefaction, transportation and regasification.

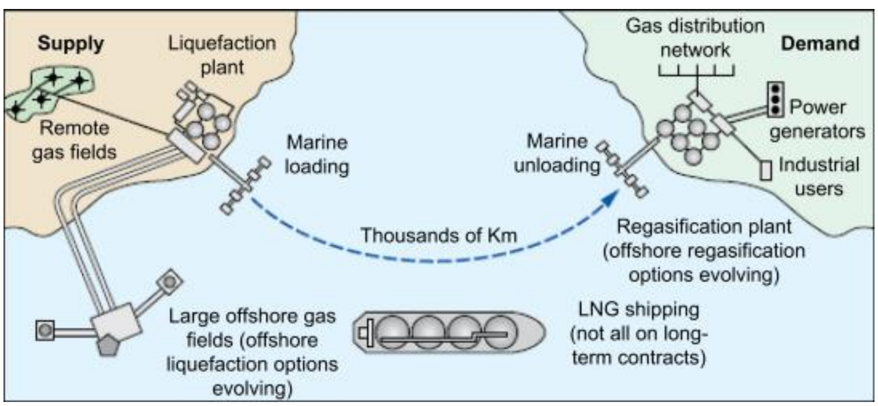

Figure 2 Diagram of the LNG production and supply chain [4]

2.2. Natural gas liquification

The most energy-consuming process in the LNG production chain is gas liquefaction. Condensing technology is based on the principle of refrigeration cycles. The natural gas must be cooled to the saturation temperature, which is approximately -160 °C at normal pressure. Existing liquefaction technologies are based on three basic methods [4, 5, 6]:

- Classic cascade cycle,
- A cycle with a mixed refrigerant,
- Expansion cycle using a turboexpander.

Condensing 1 kg of natural gas requires an average consumption of 1.2 MJ of energy for liquification. This demand for energy is covered by burning about 8% of the natural gas supplied to the LNG factory [4]. Part of the energy used in the liquefaction of natural gas is stored in LNG as cryogenic exergy. This exergy can be partially recovered in the regasification process.

2.3. Natural gas liquification

The task of the regasification terminal is to bring the LNG into the gas state and inject it under the required pressure to the network of transmission pipelines. LNG discharged from ships is first sent to insulated tanks, where it is stored under a slight overpressure at a temperature several degrees below the evaporation temperature. Because of the heat source the regasification method selected by LNG can be divided into the following groups [4]:

- ORV (Open Rack Vaporizers), STV (Shell and Tube Vaporizers),
- AAV (Ambient Air Vaporizers),
- SCV (Submerged Combustion Vaporizers),
- IFV (Intermediate Fluid Vaporizers).

2.4. Natural gas liquification

In conventional regasification processes, all cryogenic exergy stored in LNG is transferred into seawater or other factor serving as an external heat source and lost. However, it can be partially recovered. There are many concepts for the use of LNG cryogenic exergy. They can be divided into two groups. The methods of the first group are based on the direct use of low LNG temperature. Among the possible applications are: condensation and air separation, food industry (food cooling or freezing), air conditioning, cryogenic desalination of seawater or utilization in various industrial processes, e.g. in petrochemistry [6]. Low temperature LNG can also be used for cooling condensers in Rankine cycle-based plants or for cooling compressed air in gas turbine cycles. The second group of methods is based on the use of LNG cryogenic exergy for the production of electricity. Liquefied natural gas can be used as the lower heat source in thermodynamic cycles or directly as a circulating medium. Most common methods are [7]:

- Direct expansion cycle (DEC),
- Rankine cycle (RC),
- Brayton cycle (BC),
- Kalina cycle,
- Stirling engines.

2.5. LNG import and export

Figure 3 shows the LNG export volumes by all 18 countries that in 2017 participated in the global LNG market on the suppliers' side.

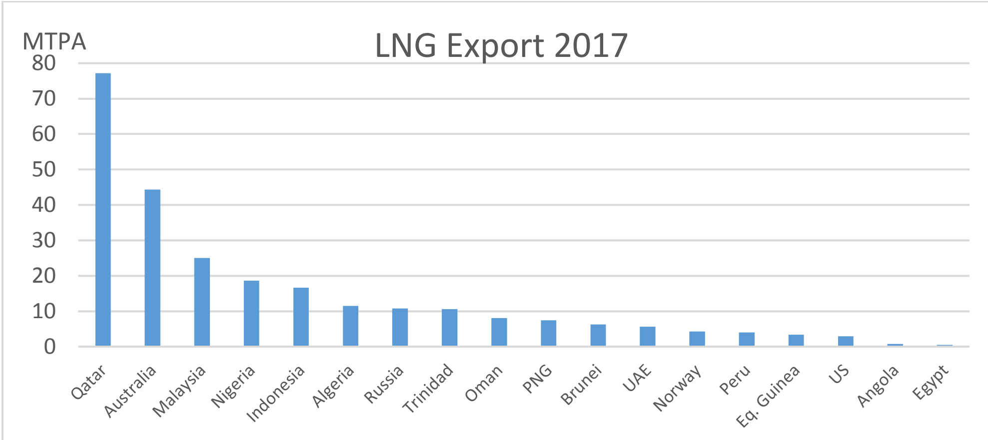

Figure 3 Global LNG Export in 2017 [5]

In 2017, 35 countries participated in the global LNG market on the recipients' side. Figure 4 presents the volumes of LNG imports by individual countries.

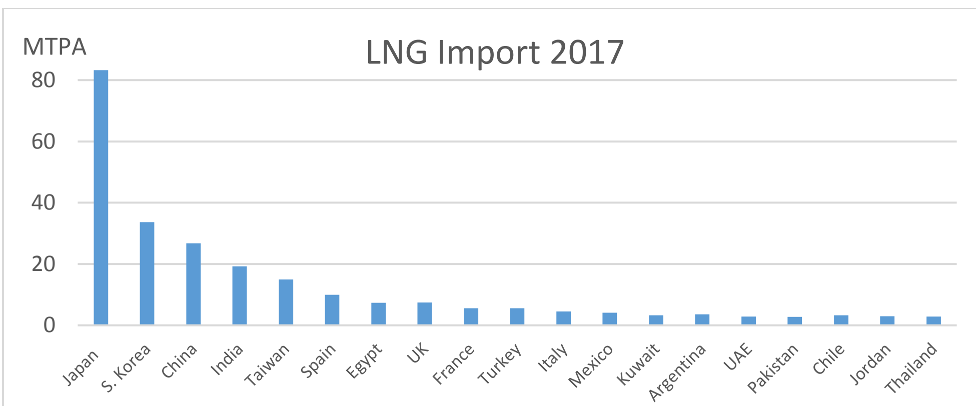

Figure 4 Global LNG Import in 2017 [5]

3. Exergy

3.1. Definition of exergy

The concept of energy is not a sufficient criterion to describe the practical utility of its various carriers, as evidenced by the fact that streams of compressed and not compressed air, having the same temperature, transport the same amount of energy due to the fact that the enthalpy of air depends a little from a pressure. Therefore, the concept of exergy has its origin in the second law of thermodynamics, according to which each thermodynamic change proceeds towards increasing entropy, and thus it is accompanied by losses associated with the irreversibility of the process. As a result, it became possible to characterize different energy carriers in terms of quality, not only quantitative, because exergy determines the ability to transform different forms of energy into other ones. It is important that the practical energy usefulness of matter is equal to zero when it is reduced to a state of thermodynamic equilibrium with the surrounding nature. Thus, the surrounding nature is a kind of zero point - a reference in the exergy analysis [8].

Finally, the following definitions of exergy were adopted:

- *Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes [9].*
- *The minimum work needed to raise system from the reference state to the system state* [9].

The total exergy of the substance stream consists of: B_k kinetic exergy, B_p potential exergy, B_f physical exergy, B_{ch} chemical exergy, B_j nuclear exergy, other exergy components.

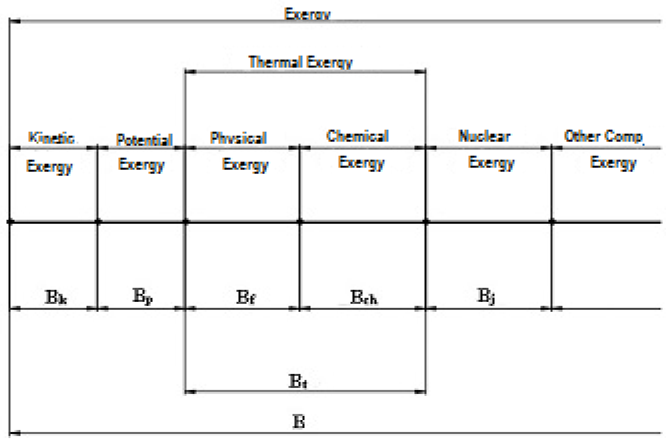

Figure 5 Exergy components of the substance stream [9]

The physical exergy is zero if the substance has an ambient temperature as well as ambient pressure. However, when a substance with these parameters has a chemical composition that is not compatible with the composition of bodies commonly found in the environment, the substance is characterized by a non-zero and usually a positive value of chemical exergy. The inclusion of chemical exergy is necessary in the case of analysis of processes during which the substance is exchanged with the environment [9].

3.2. Calculation of exergy

As in the case of energy, the exergy can be divided into the internal relating matter within system boundary, and the flow leaving the system boundary. From a practical point of view, flow exergy is more important because most of the analysed devices are flow-through. Flow exergy can be divided into several components, which include: kinetic exergy, potential exergy.

Physical exergy expresses a decrease of exergy in a situation when the tested substance differing in temperature and pressure in relation to environmental parameters will be reduced to these parameters.

The physical exergy can be divided into a temperature part and a pressure part in the considered parameter range. However, this applies to substances that are not subject to phase changes during a given process. The temperature section is always positive, because cooling the substance to a temperature below the ambient temperature increases the value of the exergy.

4. Exergy cost analysis

Determining the exergy cost allows to check how the individual components of a separate system work and interact with each other. This gives information about what losses are generated in devices, and how these imperfections affect the work of others. Thanks to this, it is possible to determine if the changes in operation have a beneficial or negative effect on the operation of the devices and how these changes affect the imperfection of the processes occurring in the separate components of the system. It may happen that as a result of changes a given component has improved its performance, thus causing deterioration of working conditions in another. One should therefore strive for a state in which the losses of exergy during particular stages of the production process are minimized. However, it is not possible to strive at all costs to reduce these imperfections, as limiting losses should go hand in hand with measurable financial benefits.

The calculation of the consumption of exergy in the selected component is connected with the necessity to create an exergy balance and to determine the exergy efficiency of the device.

5. Exergy diagnosis

Diagnosis is a field dealing with the recognition and examination of changes in industrial facilities during their operation. Its task is to locate the place and the causes of the emerging imperfections in cycle, as well as to improve the efficiency of the irreversible process analysed. In addition, the diagnosis allows to check what is the impact of the malfunctioning device on the remaining components of the separated system, and to show how losses are generated in the cycle of thermodynamic processes in a given technological process. For this purpose, it is necessary to know the best about several operational states of the system, with one of these states being so called reference, and therefore working with the highest possible efficiency, and thus with limited losses. Other states, called operational, are most often created as a result of deterioration of the parameters of the reference condition. The reference state is thus a reference point in the thermoeconomic analysis with which the other operating conditions of the system can be compared [10].

6. CCGT plant and CCGT plant with LNG regasification

Combined Cycle Gas Turbine are one of the most popular power and combined heat and power plants worldwide. This is mainly due to their high efficiency, availability and flexibility. They are simply a combination of open-cycle gas turbine with steam cycle which has heat recovery steam generator instead of a boiler.

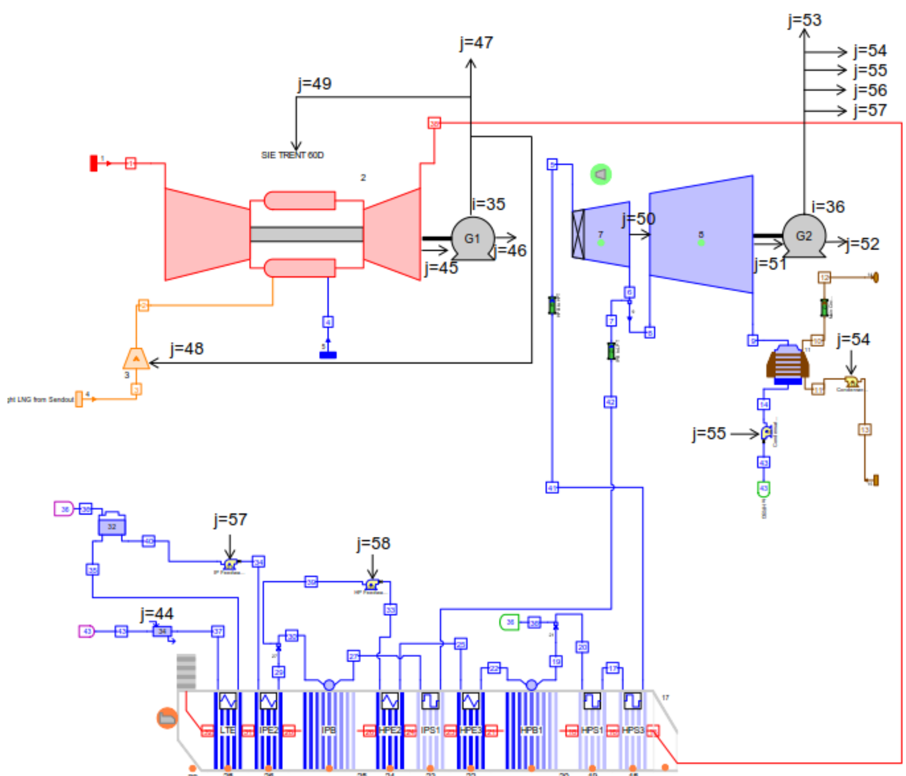

Figure 6 Combined Cycle Gas Turbine system with all exergy flows defined

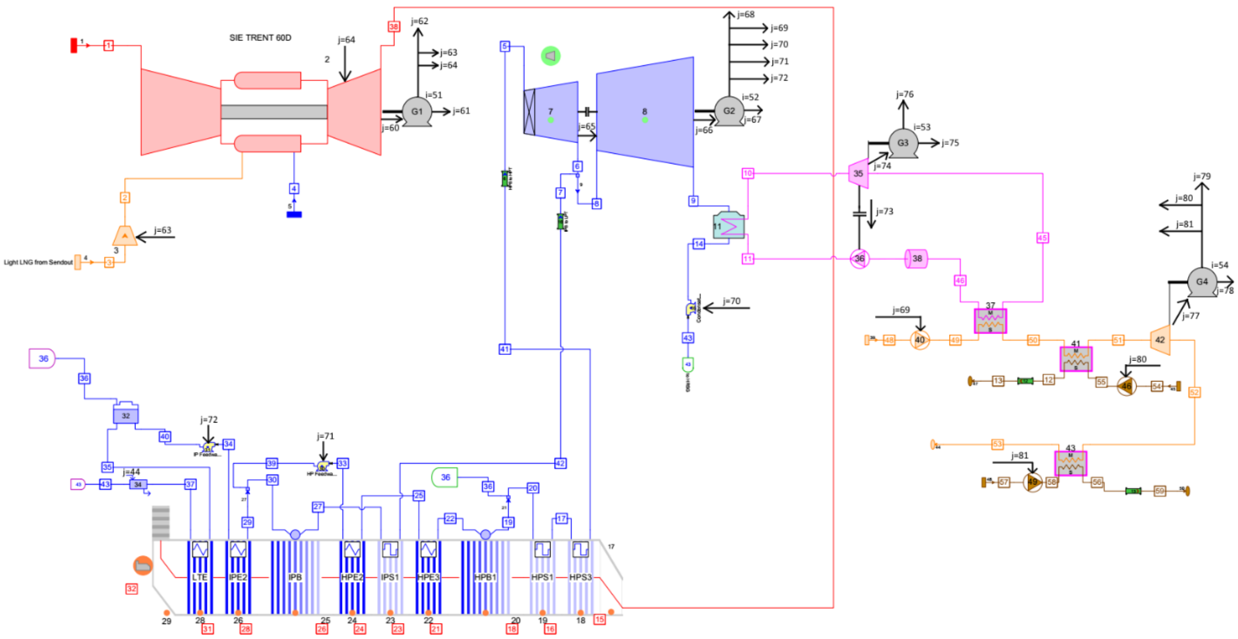

Figure 7 CCGT integrated with LNG regasyfication system with all exergy flows defined

Presenting the simplified operation of a given system: a stream of air and natural gas is supplied to the combustion chamber of the gas turbine generating a combustible mixture, which then causes combustion of high temperature flue gases at increased pressure. These fumes are then directed to the gas turbine, where as a result of their expansion, mechanical power is generated on the shaft, resulting in driving the compressor and the generator. In addition to electricity generated at the terminals of the generator, from the gas turbine set, exhaust fumes are fed to the boiler (Heat Recovery Steam Generator), whose task is to heat the feedwater, evaporate it and overheat the steam generated, which is then fed to a steam turbine. In turn, in this component, as a result of steam expansion, mechanical power is generated that drives the generator, as well as low-temperature and low-pressure steam supplying the condenser. Condensate leaving the condenser goes to the feedwater pump, thus increasing the pressure. Water with increased pressure goes to the recovery boiler, thus closing the gas-steam cycle. However, heat from the condenser is not rejected to the environment but used to regasify liquefied natural gas. CCGT cycle and LNG cycle are interconnected by an ammonia cycle which serves a role in increasing thermodynamic efficiencies (reducing imperfections) of a whole plant by gradually reducing temperature difference (pinch) between LNG and steam condensate. What is more application of ammonia intermediate cycle is dictated by material and fluid properties. It is hard to find right fluid to suit that temperature range. The lowest cycle is LNG cycle which is similar to as-called in literature direct expansion + sea water heating regasification. The difference consists in utilizing additional heat supplied by ammonia cycle, coming from CCGT cycle.

7. Conclusions

As part of this work, the focus was on the method of transporting natural gas in liquefied form (LNG). The LNG production and supply chain as well as the current state of the global market for this fuel were described. The methods of regasification of LNG and the possibility of recovery of cryogenic exergy stored in it have been reviewed. The concept of exergy and exergy cost analysis has been described.

The main element of the work was the implementation of mathematic models of two Combined Cycle Gas Turbine systems in proper software and then their thermoeconomic analysis, with the difference that one of them was integrated with LNG regasification.

As part of the conducted diagnosis so-called matrix method has been presented. This method allows the analysis of even very complicated systems, such as the presented CCGT power plant. The first stage of the calculations was to model the system in the Thermoflex 26 [1] software, where two operating states were created - reference x_0 and operating x_1. The first of the states was characterized by the highest perfection of processes going in the system, while the second resulted from the deterioration of the working conditions of selected components. After the simulation, a full set of parameters for each stream was obtained, which in turn allowed to determine the value of exergy at these points - after importing simulation results into Microsoft Excel linked to Cool Prop [2] and REFPROP [3] databases. Finally, after obtaining the exergy value at each of the points in the system, a matrix analysis was carried out using the Microsoft Excel calculation sheet. All following stages of thermoeconomic analysis were shown on the example of a simple CCGT plant, explaining all the mathematical operations.

Algorithm for calculations of CCGT plant integrated with LNG regasification should have been theoretically identical as for simple CCGT plant. However, obtained results were very doubtful. Calculations have been checked extensively and it was concluded that the proposed method is not adjusted for such a specific case. The case of CCGT plant integrated with LNG regasification was found to be unique due to the fact that for some system components thermodynamic processes have been crossing ambient temperature. Due to special behaviour of exergy in temperatures below ambient, it is usually very hard to define so called (in matrix method) fuel and product. In such a specific case fuel and product may be shifting between themselves but not completely. They may shift just in part which could not have been implemented in matrix method which requires unambiguous and binary definition of fuels and products. However, it only prevented carrying out of exergy diagnosis, but exergy and exergy cost analyses have been conducted successfully.

Analysing the results obtained for simple CCGT plant was observed that the lowest exergy efficiency, and consequently the highest specific exergy cost is bounded to condensate pump. However, it is worth noticing that absolute exergy loss of that component is not a significant part of all exergy losses compared to components like gas turbine, fuel compressor or steam turbine. The reason for small exergy efficiency of condensate pump is its low adiabatic efficiency equal to 14.57%. High exergy cost gas turbine, fuel compressor and steam turbine are due to irreversibility of ongoing thermodynamic processes.

On the other hand, for simple CCGT plant, the smallest specific exergy cost, close to one, is characterized by flow splitters, a mixer, pipelines and flue gas duct from Gas Turbine to HRSG. In turn, the exergy cost of pipes and flue gas duct from Gas Turbine to HRSG is close to one, since relatively small pressure losses translate into insignificant losses of exergy.

Analysing the results obtained for the simple CCGT plant, it can be seen that as a result of the introduced changes in the system, the value of exergy of fuel delivered to the cycle increased while exergy of useful products (net electricity) was kept the same. The component that is characterized by the highest increase in fuel consumption in both reference and operational state is the gas turbine. It can also be concluded that several components have reduced the value of fuel exergy, an example of which are components such as 18 and 19 (heat exchangers of HRSG) and generator number 2. There is no change in exergy delivered to steam turbine as steam parameters entering the turbine parts was set rigidly.

Conducting thermoeconomic analysis is a convenient and transparent way to diagnose the chosen system. It can be stated how the deterioration of the operation of one component affects the operation of the entire system, and in particular what are the consequences of this in relation to the operation of other devices identified in the analysed cycle. In addition, this analysis may serve as an excellent optimization tool, as it is possible, as in the present case, to distinguish several operating states characterized by changed parameters, and then to check which one works in the most effective way, and therefore where the losses of exergy are the smallest and where it is observed the lowest consumption of fuel exergy. In addition, this analysis is particularly important in the era of care for the environment and exhaustible natural resources. However, one should be especially careful if the chosen method for thermoeconomic analysis works properly for any cycle and for any temperature range.

By comparing the simple CCGT plant with the CCGT plant integrated with LNG regasification by the means of energy performance it was shown that energy efficiency of the cycle can be increased by 1.9% while decreasing LNG consumption for regasification in SCV regasifiers by 1.5%. What is more energy recovered from LNG allows to drive LNG pumps providing energy that would otherwise have to be supplied from outside. Such a solution leads to a reduction in energy consumption as well as emissions reduction. However, any improvement to energy systems should have not only be justified by thermodynamics, but economy as well.

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