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Theoretical analysis of LNG regasifier supplementing gas turbine cycle

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Abstract Liquefied natural gas (LNG) is transported by the sea-ships with relatively low pressure (0.13–0.14 MPa) and very low temperature (about 100 K) in cryo-containers. Liquid phase, and the low temperature of the medium is connected with its high exergy. LNG receives this exergy during the liquefaction and is related with energy consumption in this process. When the LNG is evaporated in atmospheric regasifiers (what takes place in many on-shore terminals as well as in local regasifier stations) the cryogenic exergy is totally lost. fortunately, there are a lot of installations dedicated for exergy recovery during LNG regasification. These are mainly used for the production of electricity, but there are also rare examples of utilization of the LNG cryogenic exergy for other tasks, for example it is utilized in the fruit lyophilization process. In the paper installations based on the Brayton cycle gas turbine are investigated, in the form of systems with inlet air cooling, liquid phase injection, exhaust gas based LNG evaporation and mirror gas turbine systems. The mirror gas turbine system are found most exegetically effective, while the exhaust gas heated systems the most practical in terms of own LNG consumption.

Keywords: LNG; Gas-turbine; Cryogenic exergy; Exergy recovery

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1 Introduction

The transport of gas in the form of liquefied LNG – liquefied natural gas) is an alternative to traditional pipeline transport. Trade-in liquefied LNG in 2013 remained stable, reaching 236.8 million tonnes (in 2012–237.7 million tonnes) [1]. Qatar was by far the world's largest LNG supplier, while Japan remains the dominant importer worldwide (37% of global imports). The global nominal capacity of gas liquefaction installations in 2013 reached the level of 290.7 million tonnes/year. The share of natural gas in global energy consumption is about 25%. Since 2000, a continuous increase in the share of LNG in meeting the demand for natural gas has been observed. Currently, this share is estimated at 10% [1]. Among European countries, Spain, the United Kingdom and France are the largest importers. However, total LNG imports to Europe remain much smaller than in Japan. New investments in LNG unloading terminals are still planned, including the Polish terminal in Świnoujście.

The planned capacity of the Polish terminal in Swinoujscie is about 4 million tons per year. Assuming that this potential is used in a simple cryogenic power plant with parameters $N = 1000$ kW with an LNG stream feeding the power plant 40 t/h and gas pressure sent to the network at 30 bar, available cryogenic exergy of gas would generate about 100 GWh of electricity per year. Accurate estimation of electricity production potential based on engines using LNG cryogenic exergy requires detailed thermodynamic, ecological and economic analyses in the field of available energy technologies to recover cryogenic LNG exergy. Indeed, the use of these technologies leads to the following beneficial effects:

- reduction of cumulative energy consumption of LNG gas imports,
- reduction of specific CO_2 emissions charged for imported LNG,
- improving economic efficiency in the field of LNG imports.

1.1 Cryogenic power plant technologies

Liquefied natural gas is stored at a cryogenic temperature of $-165°$C and a pressure close to ambient pressure. LNG acquisition is burdened with relatively high energy consumption in the range of 1370–1485 kJ/kg [2]. Due to the low temperature, liquefied LNG gas is characterized by relatively high physical cryogenic exergy. In the regasification process, the potential of available exergy is estimated at about 400 kJ/kg [3, 4]. This value can appear small compared to the chemical exergy of methane, 51807.98 kJ/kg, however, it is too large to allow it to be irreversibly lost. An example of determining cryogenic (temperature) exergy in [4] is shown in Fig. 1, on a temperature-entropy diagram. The letters denote A – saturated low-pressure liquid, B – high-pressure liquid, C – saturated high-pressure liquid phase, D – saturated high-pressure vapour phase, E – superheated gas.

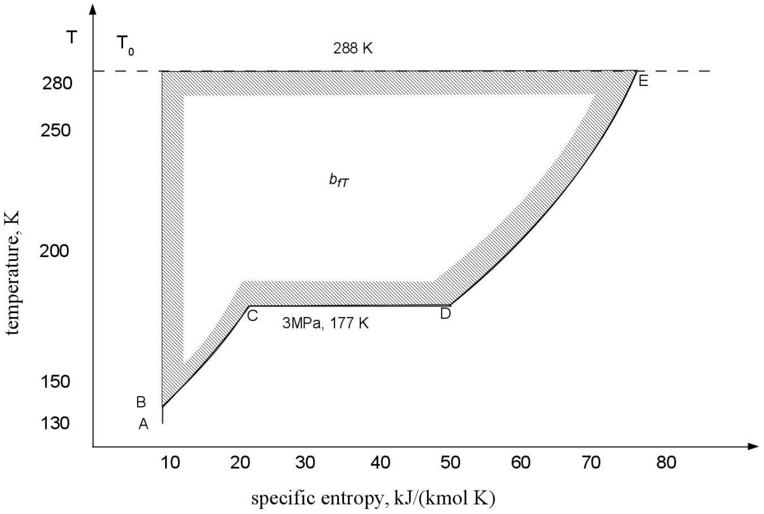

Figure 1: Temperature part of physical LNG exergy [4].

For parameters from Fig. 1, the temperature part of the LNG exergy (without considering the potential resulting from higher pressure) is 425 kJ/kg, which is less than 1% of the chemical exergy of natural gas. However, given the large volumes of LNG transshipped, physical exergy represents the excellent potential for electricity generation. This exergy is released into seawater or another medium serving as an external heat source in a conventional regasification process. Cryogenic exergy of liquefied LNG gas can be used to drive a so-called cold engine, cool condensers in traditional power plants based on the Rankine cycle, or cool compressed air in gas turbine circuits. Cryogenic exergy, in addition for the production of electricity, can generally also be used for the following processes [3]:

- in the process of liquefaction and air distribution,
- in the food industry for storing and freezing food,
- in the process of desalination of sea water,

- in air-conditioning processes,
- in industrial processes, e.g. petrochemicals.

In recent years [3–26], special emphasis has been placed on research in the field of application of cryogenic exergy to drive cold engines or integration with engines powered from high temperature sources. In particular, the following energy technologies are considered as power plants powered by LNG exergy:

1) direct LNG expansion (open Rankine cycle) (DEX),
2) Rankine cycles (RC),
3) Brayton cycles (BC),
4) combined cycles (CC),
5) power plants based on the Kalina cycle (KC),
6) power plants based on Stirling engines.

Many examples of the aforementioned systems utilizing the cold exergy of LNG have been proposed, and some have also been built and implemented in practice. Maertens already in 1986 refers to 14 cryogenic power plants working in Japan [5]. The plants reviewed by him were of the organic Rankine cycle (ORC) type. Qiang *et al.* [6] proposed a hybrid system based on an ORC bottomed with a direct NG expansion system. That is, the proposed cycle consisted of a low-grade heat source driven, single expansion ORC, the condenser of which was to be used to vaporize the LNG, before this gas being directed to another heat exchanger using the same heat source, further to an expander and then to the gas consumer.

On the other hand, Kim *et al.* [7] proposed much simpler systems, utilizing a single ORC loop with different fluids, seawater as the heat source, and evaporating LNG as the heat sink. Griepentrog *et al.* [9] have proposed systems using gas turbine cycles utilizing the potential of cold exergy of LNG to increase efficiency and to use those cycles in regasification. Krey [10] proposed the use of closed-cycle gas turbines for LNG evaporation. The scheme envisages the use of LNG as a cooling fluid in the heat sink of the turbine. Different working fluids were considered. It is also important to note that the system was estimated to have good efficiency at partial loads. Arsalis *et al.* [11] proposed the use of LNG in distributed energy regasification systems. They have proposed trigeneration systems based on different technologies depending on the output, including gas turbines, gas engines, steam turbines for the generation of electricity, and further the use of absorption chillers working of the engine waste heat as the means of cooling.

Furthermore, the use of waste heat from power generations has been proposed to produce useful heat. The cold exergy of the LNG in the systems they suggested could be utilized directly in the cooling networks or by cooling the intake air for gas turbines. Hepbasli *et al.* [27] have proposed and analysed a diesel-gas engine system for an industrial estate zone in Turkey. They have provided a conventional exergy analysis of such a system, which could be extended if LNG were used. Zhang *et al.* [12] proposed a system based on the supercritical carbon dioxide cycle coupled with LNG cold exergy and an organic Rankine cycle utilizing the LNG as a working fluid, working as a heat sink for the SCO_2. The authors have examined the cycle using conventional thermodynamic analysis. Subramanian *et al.* [13] investigated the potential of using LNG regasification cold exergy in cooling grids in Singapore. The authors have proposed to use the recovered exergy in commercial and residential applications, and a convention exergy analysis has been performed in their work. Wang *et al.* [14] analysed a combined system utilizing LNG, a Rankine cycle and a Brayton cycle and an ejector based cooling system. LNG has been used as a heat sink to condense the steam of a Rankine cycle, cool the gas turbine intake, and then it would flow as fuel into the gas turbine combustion chamber. The authors have provided a rudimentary exergy analysis. Kaneko *et al.* [21] have proposed a mirror gas turbine cycle, where the compressor is mirrored, working effectively as a vacuum pump, pumping cooled air out of the system. This was proposed with LNG evaporation in mind and shown as a standalone cycle, or a bottoming component for LNG fired Brayton plants. Mehrpooya proposed a system integrating LNG, a steam turbine power plant and fuel cells [15]. This system was designed for gas liquefaction instead of regasification, though it can provide some insights.

The basis for the system is utilizing a gas-driven hybrid fuel-cell-steam-turbine plant and utilizing the waste heat for gas refrigeration through an absorption chiller. Some of the electric power is also utilized. The authors carry out a detailed exergy balance of the system. Kowalska and Pazdzior [16] proposed utilizing the cold exergy of LNG in micro-cogeneration and micro trigeneration in the food industry. Also, the use of Stirling cycles for small scale plants has been discussed by some authors, mainly such as Szczygieł, Buliński *et al.* [17–19]. Stirling cycles using LNG evaporation to cool down the heat sink have the additional advantage over conventional Stirling cycles since the internal heat transfer coefficients are higher at lower temperatures. In the paper, the solutions based on Brayton cycle are presented and discussed.

2 Brayton cycle power plants utilising LNG cryogenic exergy

The Brayton cycle is a cycle of gas turbines. In the basic version, it consists of two adiabatic processes (compression and expansion) and two isobaric processes during which heat is exchanged with the upper and lower heat sources. In a closed Brayton system, the inert gas selected for the operating temperature range of the cycle (e.g. N_2, CO_2, noble gases, etc.) is a more expensive and less common solution in practice. In an open system of a gas turbine, the upper heat source is a combustion chamber, in which most natural gas is burned in compressed air, then the exhaust gas is directed to the turbine and further to the environment. It is a cheaper solution and much more common in practice. In the Brayton cycle, LNG cryogenic exergy (temperature part of LNG physical exergy) can be recovered in three basic ways.

2.1 System with inlet air cooling

In an open gas turbine system, LNG can be used to cool the air directed to the compressor and further to the combustion chamber (Fig. 2). In this way, the unit work necessary to drive the compressor is reduced so that the effective power and efficiency of the entire system increases. In the system shown in Fig. 2, part of the evaporated LNG is directed to the combustion chamber of the gas turbine. The presented system is characterized by high turbine power, allowing evaporation of the LNG stream. As a result, a relatively large stream of evaporated gas is consumed in the turbine – as calculations have shown, the turbine's own needs reach up to 50% of the evaporated gas. This is due to the low temperature of the cooled intake air. Due to the low costs of turbine adaptation, such a system can be used for an existing LNG powered turbine. In this case, the modification will be replaced by replacing the atmospheric regasifier with an intake air cooler. In other cases, this arrangement appears to be economically unjustified.

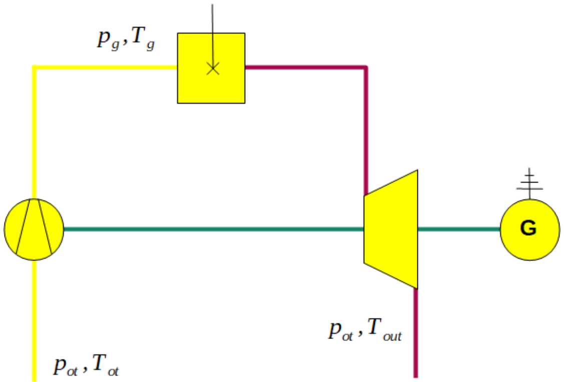

Figure 2: Turbine with inlet air cooling (p – pressure, T – thermodynamic temperature, G – electric generator).

2.2 System with inlet air and exhaust gasses cooling

Reduction of the amount of gas consumed for the needs of a regasification turbine can be easily achieved by using the exhaust enthalpy leaving the turbine. These exhaust gases have a high temperature at ambient pressure, and directing them to a regasifier reduces the turbine power required to ensure complete LNG evaporation. As a result, the stream of gas consumed for the turbine's own needs is significantly reduced. The amount of gas is reduced to several percent of the main LNG stream. The system is presented in Fig. 3. The regasifier is divided into two stages: in the first, cooling inlet

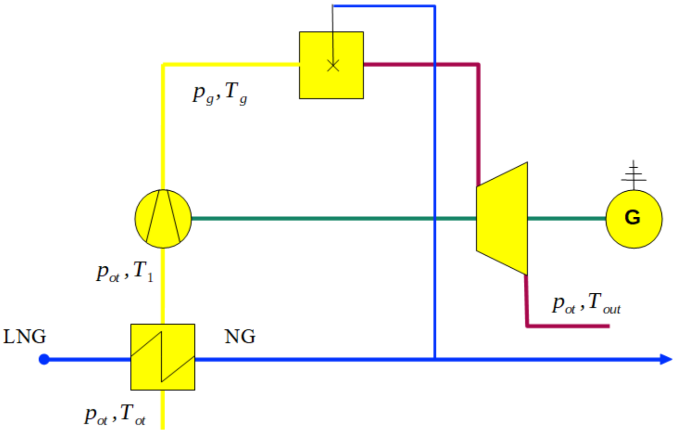

Figure 3: Turbine with inlet air and exhaust gasses cooling.

air, the LNG is heated to saturation, proper evaporation and overheating takes place in the second stage. Of course, such a system is not applicable to a turbine equipped with a heat regeneration system.

2.3 Mirror compressor system

The low temperature of evaporated LNG allows constructing a gas turbine system characterized by a much more effective degree of utilization of cryogenic LNG exergy. However, such a system is associated with greater interference in the construction of the turbine and, thus, associated with increased investment costs. Turbine operation strongly depends on the exhaust pressure, and lowering this pressure increases the compression ratio in the turbine without increasing the energy expenditure on the compressor drive. In practice, the lowest natural pressure is used, i.e. ambient pressure.

Using an additional pressure reducing compressor downstream of the turbine would lengthen the thermodynamic processes chain and thus should be unjustified from the point of view of the Second Law of Thermodynamics. However, this seemingly unjustified procedure becomes effective when the exhaust gas stream cools down between the turbine and the additional compressor. Cooling must, however, be carried out using natural or waste cold. The use of a chiller to cool exhaust gases would significantly reduce exergy efficiency. In the turbine used for LNG regasification, the stream of cryogenic exergy can be successfully used for cooling exhaust gases and thus to increase substantially both the exergy efficiency of a gas turbine and for more efficient use of the exergy of cold evaporated LNG. The discussed system is presented in Fig. 4. The regasifier was divided into three stages. In the first stage, the air flowing into the compressor is cooled. In the second, the condensate from the exhaust gas is cooled, and in the third, the mainstream of exhaust gas directed to the additional compressor is cooled down. Condensate is at a lower pressure than the ambient one, so a pump must be used to discharge them to the surroundings. Energy expenditure on the pump drive is negligible.

By changing the compression ratio in the exhaust compressor, one can freely choose the turbine outlet pressure – even values close to vacuum. As calculations have shown (Section 3.4), this pressure's optimum value depends on the main turbine operating parameters.

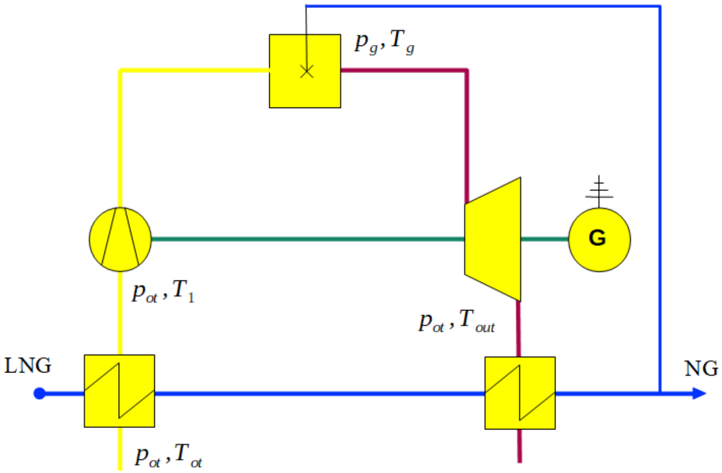

Figure 4: Mirror compressor turbine.

2.4 Mirror compressor system with liquid gas in combustion chamber

The turbine with liquid gas supply to the combustion chamber was analyzed as the last one (Fig. 5). This idea is derived from the Cheng gas-steam

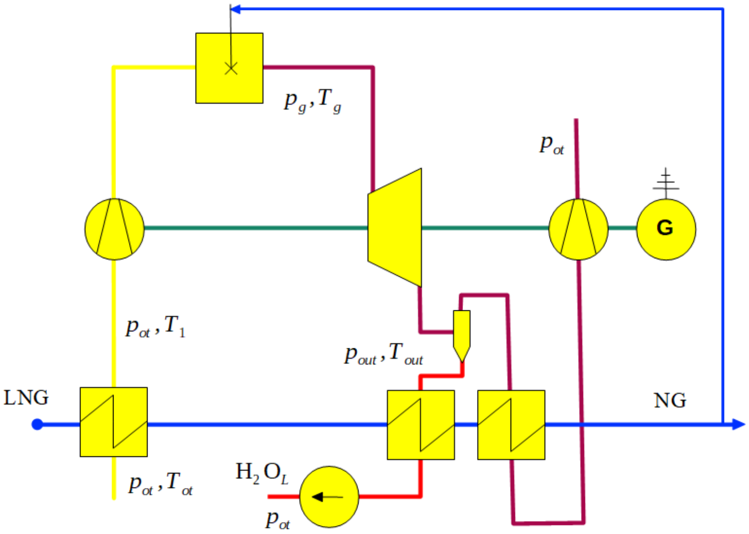

Figure 5: Mirror compression system with liquid gas injection.

combined heat and power (CHP) plant [28], where steam is supplied to the combustion chamber of the gas turbine to cool down the exhaust gases before the turbine and thus to reduce the excess air ratio in the chamber. The relatively high air excess ratio in the gas turbine combustion chamber, resulting from the limitations of the temperature of the exhaust gases directed to the turbine, contributes to the reduction of the exergy efficiency of the combustion chamber. In the proposed solution, a similar role is played by the liquid gas directed to the combustion chamber.

3 Results of multivariant analysis

To estimate the efficiency of the LNG cryogenic exergy utilization, multivariant calculations of the presented system were performed. The commercial package Ebsilon Pro was used for the calculations. The software is designed for modelling the thermodynamic cycles in various energy conversion systems. The software solves mass and energy balance calculations for a system designed by the user. The system design is done through a graphic interface. The user has the ability to set parameters of the various components of the system at will and define the boundary conditions. The following assumptions were made for the calculations:

- temperature at the turbine inlet 1200°C, 1300°C, 1400°C,
- inlet LNG temperature –158°C,
- inlet LNG pressure 30 bar,
- ambient air temperature 25°C,
- ambient pressure 1 bar,
- LNG mass flow rate 1 kg/s,
- compressors internal efficiency 0.86,
- turbine internal efficiency 0.90,

A block diagram of the calculation procedure is shown in Fig. 6.

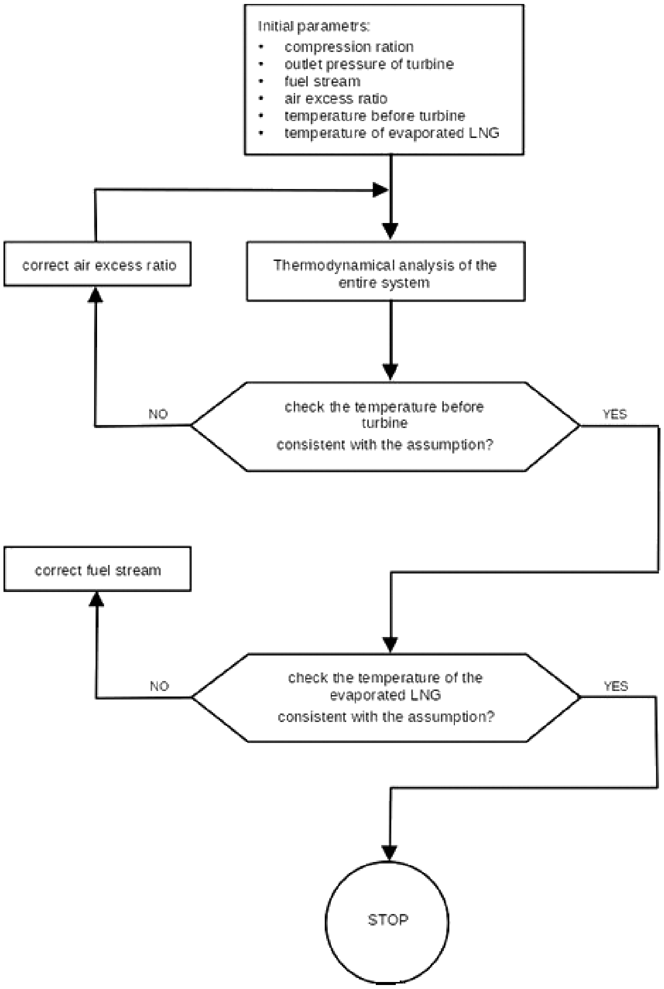

Figure 6: Calculation procedure block diagram.

3.1 Efficiency of classic Brayton cycle

Before starting the actual calculations, the influence of the compression ratio on the efficiency of the classic Brayton cycle at different working medium temperatures at the turbine inlet was analyzed. This allowed determining the optimal compression ratio for each temperature. Optimal values were later adopted when calculating the analysed systems. The impact of the compression ratio on the efficiency of a classic turbine is presented in Fig. 7. The methods for calculating Brayton cycles optimal compression ratio are well known [29]. As expected, the optimal compression ratio increases with the temperature of the gas entering the turbine.

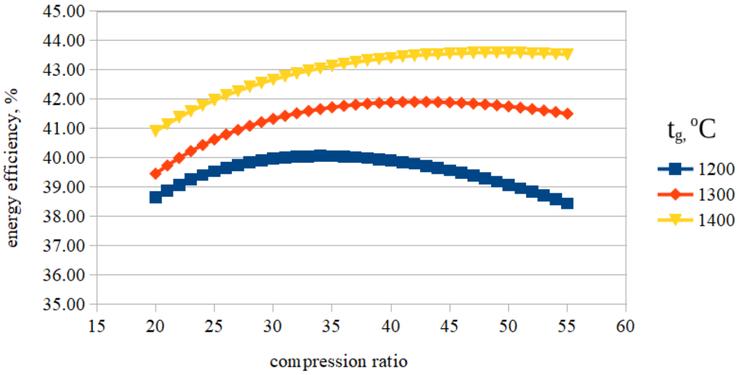

Figure 7: Calculation procedure block diagram.

3.2 Systems with inlet air cooling

As the computations showed, the fraction of LNG necessary to drive the turbine is very high – it is almost half of the main LNG mass flow rate.

$$\Delta \dot{m}_{\mathrm{LNG}} \approx 50\% \,. \tag{1}$$

The influence of the compressor inlet temperature (which results from the LNG evaporation) on the turbine energy efficiency is shown in Fig. 8.

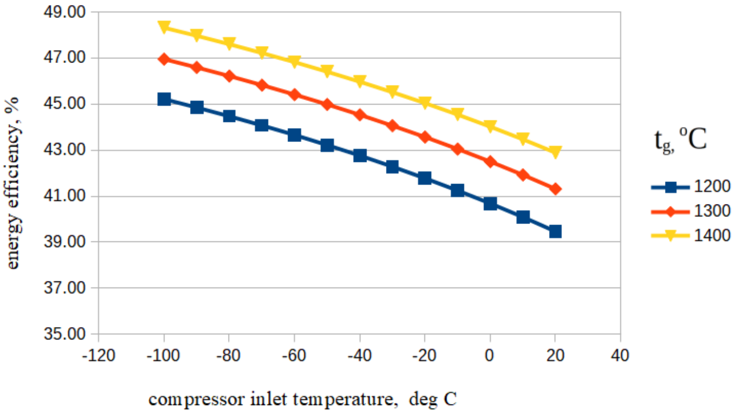

Figure 8: The influence of the compressor inlet air temperature on the energy efficiency of the turbines.

3.3 System with inlet air and exhaust gasses cooling

The amount of the LNG spent on the turbine can significantly be reduced when the turbine outlet gasses are also used for the LNG evaporation. The influence of inlet air temperature on the energy efficiency of the turbine remains the same, as shown in Fig. 8, but the fraction of LNG necessary to drive the turbine is more than ten times lower. As computations showed, it is on the level of 3%. Of course, such a system cannot be used when heat regeneration is employed within the turbine.

3.4 Mirror compressor system

Due to the fact that the system with a mirror compressor allows for the most effective use of LNG cryogenic exergy, it was given the most attention. Note that this section refers to the system shown in Fig. 4, that is without liquid phase combustion. First of all, the influence of the compression ratio on the energy efficiency of the system for the constant turbine outlet pressure was checked. The results of the calculations are shown in Fig. 9. As it can be noticed, the optimal compression ratio decreases compared to the classic Brayton cycle. It is also dependent on the highest temperature of the cycle in the same manner as in a conventional Brayton cycle.

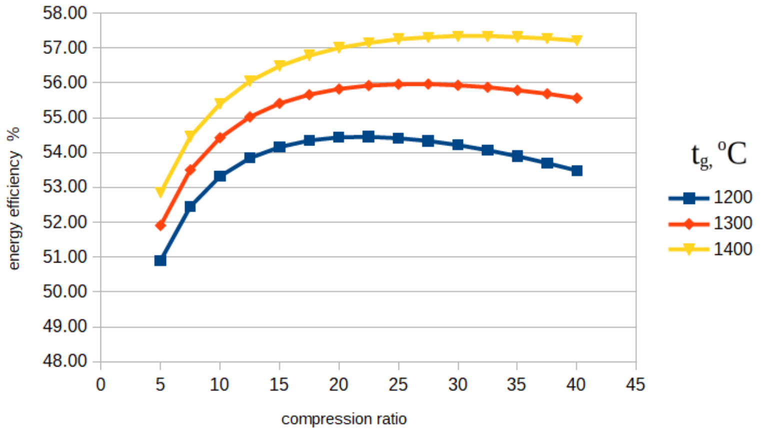

Figure 9: The influence of the compression ratio on the energy efficiency of the turbine.

In the next step, it was checked how the turbine outlet pressure affects the energy efficiency of the cycle. The results of the calculations are presented in Fig. 10. As one can see, this relationship is characterized by a clear optimum occurring in the range of low absolute pressures – at the level of 0.1 bar. Further pressure reduction results in a sharp decrease in efficiency. This can be explained by the increasing energy expenditure on the mirror compressor.

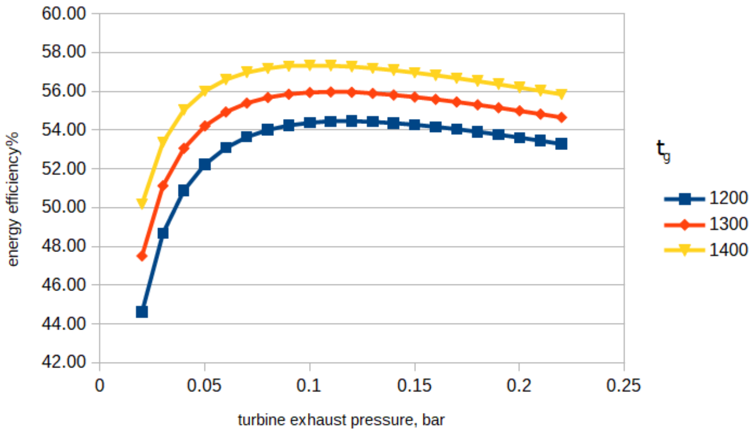

Figure 10: The influence of turbine outlet pressure on the energy efficiency of the turbine.

The calculations were carried out at the optimal compression ratios shown in Fig. 9. However, the compression ratio affects the optimum outlet pressure in the turbine. This relationship is presented in Fig. 11. It can be seen that the optimum outlet pressure increases with the compression ratio.

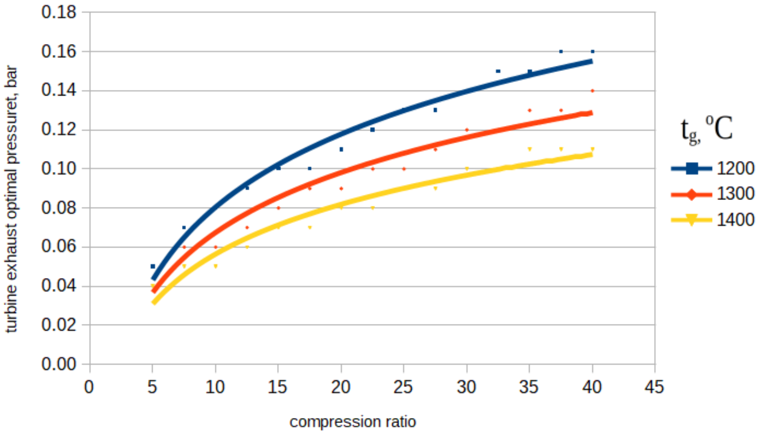

Figure 11: The influence of compression ratio on optimal exhaust pressure.

The next step was to estimate the exergy efficiency of the system. Exergy efficiency is defined as the ratio of the turbine's electrical power and driving exergy, which is the sum of chemical and cryogenic exergy supplied to the device:

$$\eta_b = \frac{N_{el}}{\dot{m}_{\mathrm{LNG}} \Delta b_{t\mathrm{LNG}} + \Delta \dot{m}_{\mathrm{LNG}} b_{ch\mathrm{CH}_4}}\,, \tag{2}$$

where: N_{el} – electric power of turbine, $\Delta \dot{m}_{\mathrm{LNG}}$ – mass flow rate of LNG spent by turbine, $b_{ch\mathrm{CH}_4}$ – chemical exergy of NG, $\dot{m}_{\mathrm{LNG}}$ – mass flow rate of regasified LNG, $\Delta b_{t\mathrm{LNG}}$ – LNG exergy change during regasification.

The influence of turbine outlet pressure on turbine exergy efficiency is shown in Fig. 12. As in the case of energy efficiency, a clear optimum can be observed, which is in line with expectations.

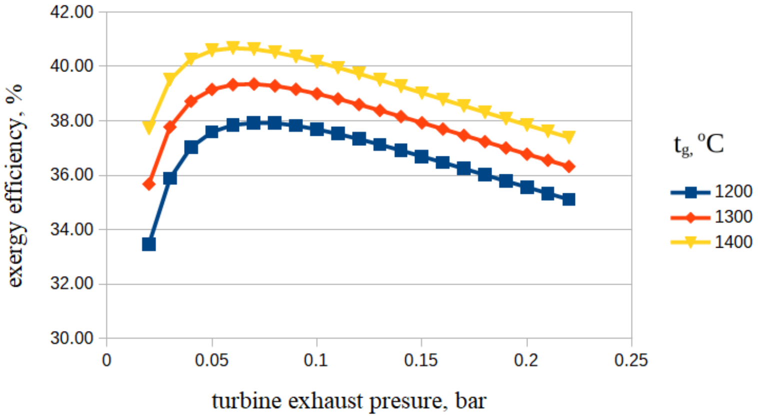

Figure 12: The influence of turbine outlet pressure on the exergy efficiency of the turbine.

Exergy efficiency defined according to Eq. (2) does not show the level of LNG cryogenic exergy utilization. Therefore, the so-called incremental efficiency, calculated in relation to a classic Brayton turbine, operating under the same conditions, i.e. with the same compression ratio and the same turbine inlet temperature was defined:

$$\eta_{\gamma B} = \frac{N_{el} - N_{el\,\mathrm{ref}}}{\dot{m}_{\mathrm{LNG}} \Delta b_{t\mathrm{LNG}}}\,, \tag{3}$$

where: N_{el} – electric power of turbine, $N_{el\,\mathrm{ref}}$ – electric power of the reference gas turbine (with the same main system parameters), $\dot{m}_{\mathrm{LNG}}$ mass flow rate of LNG regasified by turbine, $\Delta b_{t\mathrm{LNG}}$ – LNG exergy change during regasification.

The dependence of incremental exergy and turbine exhaust pressure is presented in Fig. 13. Here, too, there is a clear maximum. As one can see, the incremental exergy efficiency reaches maximum values of 40%.

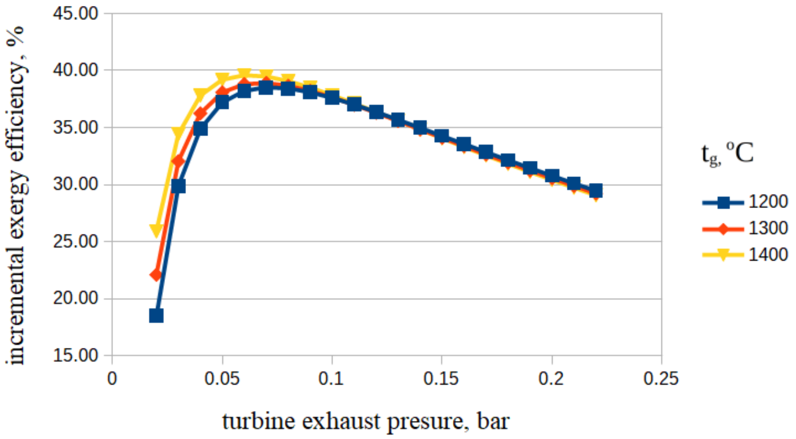

Figure 13: The influence of turbine outlet pressure on the incremental exergy efficiency of theturbine.

As the results of calculations show, the incremental energy efficiency slightly depends on the temperature of the medium before the turbine. This could lead to the conclusion that it is not worth raising this temperature. The increase of the temperature is associated with an increase in investment costs. Therefore, it was checked how the increase of the inlet temperature affects the unity power (related to 1 kg of regasified LNG) of turbine. The results of these calculations are shown in Fig. 14. It can be noticed, that increasing the inlet temperature results in unity power increment.

All presented calculations were related to 1 kg of regasified LNG. The electrical power of the system can be easily scaled, because its dependence on the LNG regasified stream is linear, as shown in Fig. 15.

Lastly, it was checked how the temperature in front of the turbine affects the fraction of the LNG mass stream taken for the turbine's own needs. The results of these calculations are shown in Fig. 16. As you can see, this fraction changes with the change of turbine outlet pressure, however its dependence on the temperature in front of the turbine is relatively weak. It follows that the temperature value before the turbine should be the result of an economic analysis taking into account the investment costs of the turbine and its electric power.

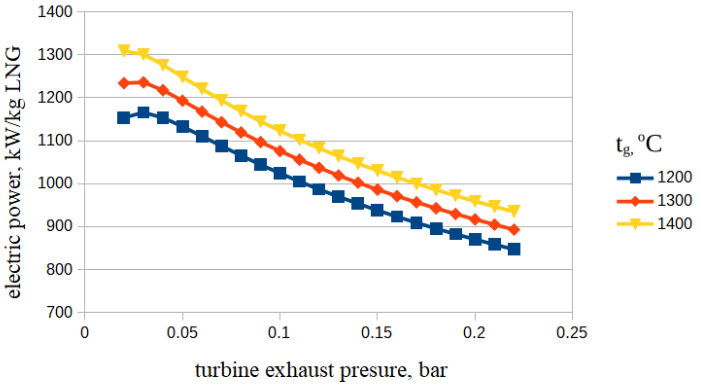

Figure 14: The influence of turbine outlet pressure on the unity electric power of the turbines.

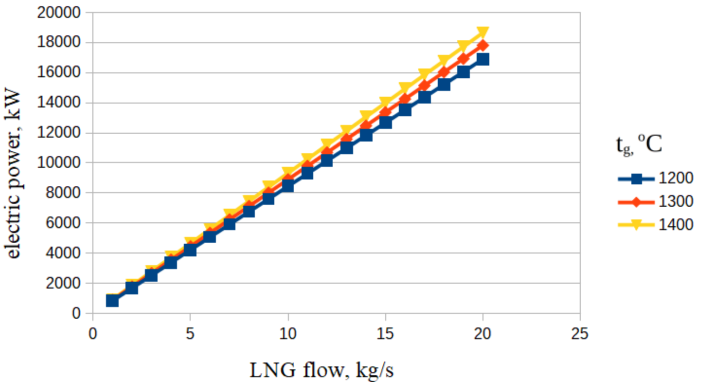

Figure 15: The influence of the LNG mass flow rate on the electric power of the turbines.

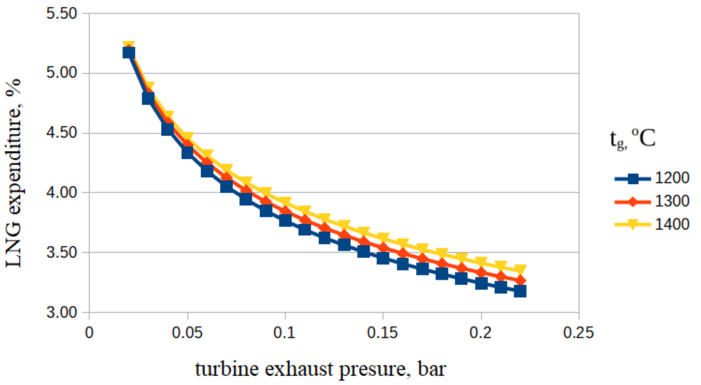

Figure 16: The influence of turbine outlet pressure on LNG fraction spent on the turbine needs.

3.5 Mirror compressor system with liquid gas in combustion chamber

Multi-variant computations confirmed the effect of feeding the liquid gas to the combustion chamber – a slight reduction of the air excess ratio can be observed. It can therefore be concluded that the exergy efficiency of the combustion chamber slightly improves. Unfortunately, the efficiency of the entire system is decreased. This can be explained by reducing the mass flow rate of flue gasses in the heat exchangers behind the turbine. Considering that the supply of liquid gas to the burners in the combustion chamber is associated with considerable technological difficulties, such an operation should be treated as unprofitable and not worth attention. Table 1 presents the change in the excess air ratio and the change in the system's energy efficiency for the pre-turbine temperature of 1200, 1300, and 1400°C.

Table 1: Influence of the liquid gas in combustion chamber on the air excess ratio (λ) and the whole system energetic efficiency (η) for different values of pre-turbine temperature (t_g).

$t_g = 1200°\mathrm{C}$			
λ_{gas}	3.168	$\eta_{en,\,gas}$, %	53.25
$\lambda_{\mathrm{liquid}}$	3.131	$\eta_{en,\,liquid}$, %	52.95
$t_g = 1300°\mathrm{C}$			
λ_{gas}	2.734	$\eta_{en,\,gas}$, %	54.66
$\lambda_{\mathrm{liquid}}$	2.703	$\eta_{en,\,liquid}$, %	54.11
$t_g = 1400°\mathrm{C}$			
λ_{gas}	2.395	$\eta_{en,\,gas}$, %	55.47
$\lambda_{\mathrm{liquid}}$	2.368	$\eta_{en,\,liquid}$, %	54.93

4 Final remarks

The paper presents and discusses the LNG cryogenic exergy recovery systems based on the Brayton cycle. In particular, three systems are presented: the turbine with inlet air cooling, the system with inlet air and flue gas cooling, and, finally, the system with mirror compressor at the outlet. The influence of main work parameters on the turbine work is presented.

As a result of the analysis, using the LNG to cool the intake air can increase the cycle efficiency but only by up to five percentage points. The only advantage of such an arrangement is that minimal modifications are needed, and a commercial, off-the-shelf gas turbine system could be utilized. Due to the high consumption of the LNG by the system, reaching values of up to 50% of the overall LNG stream is only reasonable if the gas turbine itself is to be the primary consumer of the gas. From the point of view of LNG regasification, systems utilizing the exhaust gases for evaporation are much more practical despite the lack of an efficiency gain. From the point of view of efficiency and low LNG consumption for the systems own needs, the mirror gas turbine system is the most advantageous. However, it is believed that this system would incur the most investment cost due to the necessity of installing an extra gas compressor, heat exchanger and other extra systems.

Furthermore, it was found that liquid LNG injection into the combustion chamber to lower the air excess ratio, an idea based on the principle of the Cheng cycle [28], is not thermodynamically advantageous. It also has to be added that such a cycle would incur a high extra investment cost due to the necessity of combustion chamber modification. It is also understood that it could prove to be dangerous in use.

As it results from the presented analysis, coupling the Brayton turbine with the LNG regasification can significantly increment the turbines energy efficiency, even up to almost 60%. What is also essential, the adaptations of the commercial turbines is possible. It results from the fact that adaptations of the turbine for the regasification tasks are not very deep; it can be done by adding some external devices (heat exchangers, compressors) to the commercial devices. It can significantly reduce the investment costs of adaptation.

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References

[1] IGU IGU. *World LNG report.* International Gas Union (IGU), Barcelona 2017.

[2] Khan M.S., Lee M.: *Design optimization of single mixed refrigerant natural gas liquefaction process using the particle swarm paradigm with nonlinear constraints.* Energy **49**(2013), 146–155.

[3] Romero Gómez M., Ferreiro Garcia R., Romero Gómez J., Carbia Carril J.: *Review of thermal cycles exploiting the exergy of liquefied natural gas in the regasification process.* Renew. Sust. Energ. Rev. **38**(2014), 781–795.

[4] Szargut J., Szczygieł I.: *Utilization of the cryogenic exergy of liquid natural gas (LNG) for the production of electricity.* Energy **34**(2009), 7, 827–837.

[5] Maertens J.: *Design of Rankine cycles for power generation from evaporating LNG.* Int. J. Refrig. **9**(1986), 3, 137–143.

[6] Qiang W., Yanzhong L., Jiang W.: *Analysis of power cycle based on cold energy of liquefied natural gas and low-grade heat source.* Appl. Therm. Eng. **24**(2004), 4, 539–548.

[7] Kim C.W., Chang S.D., Ro S.T.: *Analysis of the power cycle utilizing the cold energy of LNG.* Int. J. Energ. Res. **19**(1995), 9, 741–749.

[8] Chiu C.-H., Cords M., Kimmel Ohishi M., Kikkawa Y.: *Efficient power recovery in LNG regasification plants.* In: Proc. 11AIChE Spring Meeting and 7th Global Cong. on Process Safety, Chicago, March 13-17, 2011.

[9] Griepentrog H., Sackarendt P.: *Vaporization of LNG with closed-cycle gas turbines.* In: Proc. ASME 1976 Int. Gas Turbine and Fluids Engineering Conf., New Orleans. March 21-25, 1976. V01AT01A038.

[10] Krey G.: *Utilization of the cold by LNG vaporization with closed-cycle gas turbine.* ASME J. Eng. Power. **102**(1980), 225–230.

[11] Arsalis A., Alexandrou A.N.: *Effective Utilization of Liquefied Natural Gas for Distributed Generation.* Nova Science, 2015.

[12] Zhang H., Shao S., Zhao H., Feng Z.: *Thermodynamic analysis of a SCO_2 part-flow cycle combined with an organic Rankine cycle with liquefied natural gas as heat sink.* In: Proc. ASME Turbo Expo 2014: Turbine Technical Conf. Expo., Düsseldorf, June 16–20, 2014, V03BT36A012.

[13] Subramanian R., Berger M., Tunçer B.: *Energy recovery from LNG regasification for space cooling-technical and economic feasibility study for Singapore.* In Proc. 2017 Asian Conf. on Energy, Power and Transportation Electrification (ACEPT), Oct. 24–26, 2017.

[14] Wang J., Dai Y., Sun Z., Ma S.: *Parametric analysis of a new CCHP system utilizing liquefied natural gas (LNG).* In: Proc. ASME Turbo Expo 2010: Power for Land, Sea, and Air, Glasgow. June 14–18, 2010, 77–86.

[15] Mehrpooya M.: *Conceptual design and energy analysis of novel integrated liquefied natural gas and fuel cell electrochemical power plant processes.* Energy **111**(2016), 468–483.

[16] Kowalska M., Paździor M.: *LNG as an alternative fuel for food industry.* Przemysł Spożywczy **71**(2017) (in Polish).

[17] Szczygieł I., Stanek W., Szargut J.: *Application of the Stirling engine driven with cryogenic exergy of LNG (liquefied natural gas) for the production of electricity.* Energy **105**(2016), 25–31.

[18] Buliński Z., Szczygieł I., Krysiński T., Stanek W., Czarnowska L., Gładysz P., Kabaj A.: *Finite time thermodynamic analysis of small alpha-type Stirling engine in non-ideal polytropic conditions for recovery of LNG cryogenic exergy.* Energy **141**(2017), 2559–2571.

[19] Szczygieł I. Buliński Z.: *Overview of the liquid natural gas (LNG) regasification technologies with the special focus on the prof. Szargut's impact.* Energy **165**(2018), 999–1008.

[20] Stanek W., Simla T., Rutczyk B., Kabaj A., Buliński Z., Szczygieł I., Czarnowska L., Krysiński T., Gładysz P.: *Thermo-ecological assessment of Stirling engine with regenerator fed with cryogenic exergy of liquid natural gas* (LNG). Energy **185**(2019), 1045–1053.

[21] Kaneko K., Ohtani K., Tsujikawa Y., Fujii S.: *Utilization of the cryogenic exergy of LNG by a mirror gas-turbine*. Appl. Energ. **79**(2004), 4, 355–369.

[22] Bisio G., Tagliafico L.: *On the recovery of LNG physical exergy by means of a simple cycle or a complex system*. Exergy, Int. J. **2**(2002), 1, 34–50.

[23] Morosuk T. Tsatsaronis G.: *Comparative evaluation of LNG–based cogeneration systems using advanced exergetic analysis*. Energy **36**(2011), 6, 3771–3778.

[24] Morosuk T., Tsatsaronis G., Boyano A., Gantiva C.: *Advanced exergy-based analyses applied to a system including LNG regasification and electricity generation*. Int. J. Energ. Environ. Eng. **3**(2012), 1.

[25] Salimpour M.R., Zahedi M.A.: *Proposing a novel combined cycle for optimal exergy recovery of liquefied natural gas*. Heat Mass Transfer **48**(2012), 8, 1309–1317.

[26] Angelino G., Invernizzi C.M.: *The role of real gas Brayton cycles for the use of liquid natural gas physical exergy*. Appl. Therm. Eng. **31**(2011), 5, 827–833.

[27] Açikkalp E., Aras HA., Hepbaslic A.: *Advanced exergy analysis of a trigeneration system with a diesel–gas engine operating in a refrigerator plant building*. Energ. Buildings **80**(2014), 268–275.

[28] Cheng D.Y., Nelson A.L.C.: *The chronological development of the Cheng cycle steam injected gas turbine during the past 25 years*. In: Proc. ASME Turbo Expo 2002: Power for Land, Sea, and Air, Amsterdam, June 3–6, 2002, GT 2002; 421–428.

[29] Szargut J.: *Technical Thermodynamics*. Wydawn. Politechniki Śląskiej, Gliwice 2011 (in Polish).