Comparative Analysis of Power Plants Using Low Potential Heat of Liquefied Natural Gas (LNG)

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Abstract. The idea of using low-potential energy of cryogenic liquids has recently become more widespread. This is primarily due to the increasing production of cryogenic substances, as well as the general trend of energy saving and the energy potential existing in the cryoproduct in the form of energy previously used for its liquefaction.

Low-potential energy is the energy of a colder environment, having the same pressure as the consumer's energy converter. Currently, one of the most frequently used cryogenic substances is liquefied natural gas (LNG), and methods of regasification and use continue to improve.

This paper proposes a method for a comparative analysis of the use of liquefied natural gas as a working fluid, a study of the efficiency of the regasification process. The main parameters of energy installations were calculated and the main advantages and disadvantages were identified on the basis of the results, and the most optimal one was selected.

1. Introduction
Currently, natural gas is becoming one of the most important sources of energy. Natural gas in a compact form for transportation and storage may be contained in compressed (gaseous) and liquefied states. The most relevant is the use of liquefied natural gas (LNG) as an energy carrier for the same purposes as ordinary natural gas, since it allows reducing the weight and size characteristics of storage and transportation tanks.

LNG makes it possible to re-gasify objects remote from main pipelines by creating a reserve of LNG directly at the consumer, avoiding the construction of expensive pipeline systems.

In a liquefied state, natural gas at a pressure of 1 atmosphere is 600 times denser than under normal conditions. LNG makes it possible to gasify facilities remote from main pipelines by creating a reserve of LNG directly at the consumer, avoiding the construction of expensive pipeline systems.

2. Regasification process
Usually, the regasification of liquefied natural gas (LNG) occurs due to the heat of the environment. It is considered that the use of environmental heat is not an energy-consuming process. However, it should be borne in mind that considerable energy was used to liquefy LNG (about 1 kWh of electricity per 1 kg of LNG), which is simply discharged into the environment with this method of gasification. Thus, liquefied natural gas (like any other cryoproduct) contains the energy potential that could be used when it returns to its original gaseous state, and, therefore, the LNG regasification process (figure
1) itself has significant energy saving potential.

For maximum compensation of the energy spent on liquefaction, the process of regasification of the cryoproduct can be carried out using any thermodynamic (figure 2) cycle (most often, the open Rankin cycle).

3. Comparative analysis of power plants using low-potential LNG heat

To assess the effectiveness of using low-potential heat of cryogenic substances, the following parameters are used:

- **Carnot Efficiency** - a parameter showing the maximum efficiency:
  \[ \eta_{\text{Carnot}} = 1 - \frac{T_1}{T_2} \]  
  where \( T_1 \) и \( T_2 \) – are the lowest and highest temperatures.

- **Thermal efficiency** - shows the efficiency of heat conversion into the work of a cycle:
  \[ \eta_{\text{Term}} = \frac{N_{\Sigma}}{Q_{\Sigma}} \]  
  where \( N_{\Sigma} \) – the total capacity of the entire plant; \( Q_{\Sigma} \) – total heat.

- **Exergic Efficiency** - a parameter showing energy efficiency:
  \[ \eta_{\text{Ex}} = \frac{N_{\Sigma}}{E_{\Sigma \text{ex}}} \]  
  where \( E_{\Sigma \text{ex}} \) – total exergy installation of power plant.

- **Specific operation of LNG** is a parameter indicating the amount of work of a cryogenic substance (LNG) from the entire installation operation:
  \[ I_{\text{LNG}} = \frac{N_{\Sigma}}{G_{\text{LNG}}} \ast \left( \frac{E_{\text{LNG}}}{E_{\Sigma \text{ex}}} \right) \]  
  where \( G_{\text{LNG}} \) – LNG consumption in power plant; \( E_{\text{LNG}} \) – LNG exergy.

- The energy recovery coefficient of the cryoproduct - is a parameter indicating the fraction of the
return of the energy of the cryogenic substance used for gasification.

\[
k_B = \frac{W}{W_{exp} + G_{LNG}}.
\] (5)

where \(W\) - amount of energy obtained from gasification of LNG; \(W_{exp}\) – energy spent to liquefy a cryogenic substance (0.6-0.8 k\(\text{Wh}\) k\(\text{g}\)).

The objects of comparison will be the schemes of power plants that use low-grade heat LNG, described in an array of articles [1-15]. Each of the schemes uses a different thermodynamic cycle or a combination of several cycles. Also, in the schemes apply various methods of regasification of the cryoproduct. The analysis of the design features of each scheme is presented in Table 1. The estimated parameters are presented in Table 2.

Table 1. Constructive analysis analysis of power plants.

| № | heat sources                  | working fluids        | thermodynamic cycles                                      | advantages                                                                                                                                   | disadvantages                                                                                          |
|---|-------------------------------|-----------------------|-----------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------|
| [1] | Sea water                     | LNG, propane          | Closed Rankine cycle, direct extension cycle              | High rates of LNG specific work, high power, a supply of heat without burning fuel                                                        | The complicated structure, low efficiency, low energy conversion efficiency, the need for proximity to sea-water source |
| [2] | Warm environment              | LNG                   | Direct extension cycle                                    | High rates of LNG specific work, heat supply without burning fuel                                                                        | Low efficiency, low power, low energy conversion efficiency, Low efficiency, low energy conversion efficiency |
| [3] | Warm environment              | LNG, nitrogen         | Open the Rankine cycle, closed Brayton cycle              | High rates of LNG specific work, a supply of heat without burning fuel                                                                    | Low efficiency, low energy conversion efficiency                                                     |
| [4] | Secondary heat (exhaust gas)  | LNG, water            | Open and closed Rankine cycle                             | High rates of LNG specific work, high efficiency                                                                                         | Low rates of energy conversion efficiency                                                              |
| [5] | Secondary heat (exhaust gas)  | LNG, R116, R227ea     | Closed Rankine cycle                                      | High rates of LNG specific work, high rates of energy conversion efficiency                                                              | The complicated structure, low efficiency                                                               |
| [6] | Secondary heat (exhaust gas)  | LNG, water-ammonia    | Closed Rankine cycle                                      | Simple design, proven technology                                                                                                          | Low efficiency, the low energy conversion and a low share of LNG operation.                              |
| [7] | Burned fuel, secondary heat (exhaust gas) | LNG, air, nitrogen | Brayton open cycle, open and closed Rankine cycle         | The high efficiency, high energy conversion indicators and LNG specific work                                                               | Complicated construction                                                                                            |
| [8] | Burned fuel                   | LNG, water vapor      | Closed Rankine and Brayton cycle                          | High efficiency, high power                                                                                                               | The complicated structure, low efficiency, low energy conversion rates, low LNG specific work rates    |
| [9] | Solar radiation               | LNG, CO\(_2\), water vapor | Open Rankine cycle                                     | Heat supply without burning fuel                                                                                                            | Complicated construction, low efficiency, low energy conversion rates, low LNG specific work rates    |
| [10]| Secondary heat                | LNG, air, water vapor | Brayton cycle using SOFC, Rankin closed cycle             | The highest rates of energy conversion efficiency, high efficiency, high rates LNG specific work                                              | Complex construction, unprocessed production technology, part of LNG is used as fuel                  |
4. Regasification process
Comparative analysis means by a comparison of the energy characteristics of different plants (figure 3). However, it is obvious that for an installation in which heat is supplied at a higher temperature, the thermal efficiency, other things being equal, should be higher than that of an installation in which heat is supplied at a lower temperature. The criterion that shows the ratio of the level of temperatures for the supply and removal of heat is the limiting efficiency of the Carnot cycle. From the obtained values, we plotted and analyzed the point diagrams of dependences of the thermal (figure 4 a) and exergic
efficiency (figure 4 b) and the specific work of LNG (figure 4c) on the Carnot efficiency. The efficiency of the Carnot Cycle shows the ultimate efficiency of the cycle depending on the temperature level. Obviously, with a larger value of the marginal efficiency, the value of the thermal efficiency should be greater. However, the specific work of LNG does not depend on the upper temperature level, but on the parameters of the LNG state used in each specific cycle. Accordingly, it is expected that the total data array \( \eta_{\text{Term}} = f(\eta_{\text{Carnot}}) \) and \( \eta_{\text{Ex}} = f(\eta_{\text{Carnot}}) \) will be located in an ellipsoidal region, the greater semi-axis of which will have a slope corresponding to \( 0 < \frac{\eta_{\text{Term}}}{\eta_{\text{Carnot}}} < 1 \), and \( L_{\text{LNG}} = f(\eta_{\text{Carnot}}) \) - will be located in the ellipsoidal region, the large semi-axis of which is a horizontal line.

**Figure 3.** Color designation of the various proposed schemes installations using LNG.

**Figure 4.** calculation results: (a) - the dependence of the thermal efficiency and efficiency of Carnot; (b) - exergy efficiency; (c) - specific work of LNG; (d) - energy return coefficient.

Based on the results obtained, it can be noted that the dual-circuit scheme using a solid oxide fuel cell stands out from the others with the highest rates of LNG specific work, while having high efficiency. This scheme can be taken as optimal for detailed inspection.

5. Conclusion

The compiled method of comparative analysis allows to evaluate the efficiency of utilization of low-grade heat of liquefied natural gas, taking into account the peculiarities of the working process. Different installations were analyzed, general tendencies of indicators dependencies were found. The features of the working process of these plants were analyzed, their advantages and disadvantages were identified. The installation with the use of a solid oxide fuel cell turned out to be the most optimal.
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