The Natural Gas Liquefaction Technology for Small-Scale LNG

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Abstract. LNG production is an energy-consuming process, which requires significant amount of capital and operating costs. This is one of the reasons why these plants slowly spread. On the contrary small-scale LNG provides flexibility of the project and accelerates its implementation but it uses simple and ineffective liquefaction technologies. The aim of the study is to create a power-efficient small-scale LNG technology. The main tasks are review, comparative analysis and identification of energy-efficient cycles, development of technology based on the analysis of the latest technological solutions and thermodynamic calculation of the refrigeration unit. As a result, a technology based on the nitrogen cycle was developed.

1. Introduction
In the last decade, natural gas demand has grown [1,2]. This is because natural gas has lower carbon footprint than coal or oil. Besides a lot of companies is interested to build facilities which produce another form of natural gas [3]. This is liquefied natural gas (LNG). Liquid form of gas makes it easier to store and transport. However, LNG plant production has liquefaction technologies issues [4]. The problem of rational choice of technological solutions is one of the most relevant today. It requires a deep analysis and compare of production factors and innovative solutions. The study and development of the optimal LNG production technology determines the efficiency of the plant and, consequently, costs and profits [5].

2. Small-scale LNG technologies
Small-scale liquefaction plants use liquefied natural gas as a refrigerant. In this case, simpler cycles are used. There are throttling [6], expander, vortex tube [7] etc.

The basis of the technology is the use of the pressure of the supplied gas as an energy source for its cooling (Joule-Thompson effect), i.e. part of the natural gas stream acts as a refrigerant. High-pressure gas is passed through the turbines, expanded, cooled and then we get LNG at the output of the system [8].

The use of technologies of this type is typical for gas distribution plant (GDP) [9], gas-compressor station (GCS) [10], automobile CNG filling station because it is to their simplicity and relatively low operating costs [11].

In the world practice of liquefaction plants are most often used Single Mixed Refrigerant (SMR). SMR is single-circuit cooling with mixed refrigerant.
Figure 1 shows the implementation of the SMR cycle, and figure 2 shows the structure of technology use in the world [13].

These processes are effective for LNG small-scale, as cycles of this type have a large liquefaction coefficient [14].

In Russia, small-tonnage production is carried out mainly at CNG filling stations and gas distribution stations. As a result of a review of existing technologies, table 1 is compiled.

| Type of cycle               | Facility                  | Power t/h | Liquefaction coefficient, % | Specific energy consumption, kW·h/ton |
|----------------------------|---------------------------|-----------|-----------------------------|--------------------------------------|
| Throttle cycle             | GDP «Nikolskaya»          | 0.1       | 2                           | 10                                   |
| High pressure throttle cycle | CNG station, Pervoural'sk | 0.8       | 47                          | 590                                  |
|                           | GDP-1, Kaliningrad        | 1.0       |                             |                                       |
|                           | LNG plant, Pskov         | 2×1.5     | 40                          | 870                                  |
| Vortex tube cycle          | GDP «Vyborg»             | 0.5       | 4                           | 10                                   |
| Throttle ejector cycle     | CNG station-8 «Petrovorets» | 1.0     | 48                          | 360                                  |
|                           | CNG station-500 «Razvilka» | 1.5      |                             |                                       |
| Throttle-expander cycle    | GDP-4, Yekaterinburg      | 3.0       | 11                          | 10                                   |
| Nitrogen cycle (throttle-expander unit) | LNG plant, Perm region | 1.5       | 99                          | 840                                  |

According to the Table 1 we can conclude that the most effective is the nitrogen cycle. Despite of significant energy expenditures, this cycle has the highest liquefaction coefficient.

3. Proposed technology

At small-scale LNG plant in the Perm region is used an expander-compressor unit and two-stage nitrogen compression with two heat exchangers (840 kW · h / t). We developed another cycle which is presented in figure 3 below.

It is proposed to cool the natural gas (NG) by the nitrogen circuit in heat exchanger (HE2) to -161 °C. To do this, it is necessary that the temperature of nitrogen be a minimum of -165 °C (should take into account under-recovery). To effectively cool and recover part of the energy, it was decided to use the Exp expander, which can cool nitrogen by 139 °C. But, because the nitrogen temperature at the outlet of AC3 + 30 °C, and the temperature difference in Exp is insufficient for deep nitrogen cooling,
it is necessary to cool N\textsubscript{2} in front of the expander to a minimum of -26 °C. This is achieved by cooling the nitrogen circuit with a C\textsubscript{3}H\textsubscript{8} circuit.

Propane was chosen as refrigerant because of the low value global warming potential (GWP) and high cooling capacity.

4. Estimated part

It is proposed to accept the following NG parameters before HE2:

- NG temperature before HE2 - +10 °C.
- NG pressure before HE2 – 6 MPa.
- NG mass flow rate – 0.56 kg/s.
- Outlet NG pressure – 0.1 MPa.
- Outlet NG temperature – -161 °C.

In the estimations, we use the i-lgp diagram for methane, because it is close in properties to NG. Figure 4 shows the NG liquefaction scheme for the estimated technology.

**Figure 3.** The proposed scheme of the developed small-scale LNG technology: CM – compressor; HE – heat exchanger; AC – air cooler; Exp – expander; NG – natural gas.

In order to confirm the operability and effectiveness of this technology in comparison with existing ones, it is necessary to perform a thermal calculation of the refrigeration unit.

**Figure 4.** Estimated scheme of NG liquefaction in i-lgp coordinates: 1-2 - cooling with a nitrogen circuit, 2-3 - NG throttling in Exp.
The scheme contains propane and nitrogen cycles [15]. The nitrogen cycle proceeds according to the scheme in figure 5, the propane cycle - in figure 6.

**Figure 5.** $\text{N}_2$ refrigeration cycle in i-logP coordinates: 1-2, 3-4, 5-6 - compression of $\text{N}_2$ in CM1,2,3; 2-3, 4-5, 6-7 - cooling $\text{N}_2$ AC1,2,3; 7-8 - cooling N2 circuit C3H8; 8-9 - expansion of N2 in the Exp; 9-1 - cooling of the NG with a nitrogen circuit.

**Figure 6.** $\text{C}_3\text{H}_8$ refrigeration cycle in i-logP coordinates: 1-2, 3-4, 5-6 - compression of $\text{C}_3\text{H}_8$ in CM4; 2-3 - cooling $\text{C}_3\text{H}_8$ AC4; 3-4 - throttling $\text{C}_3\text{H}_8$ in choke 1; 4-4’ - share of vapor; 4-4” - liquid share.

The calculation was done according to all known methods [16]. The results are presented in table 2.
Table 2. The results of the thermal calculation of the refrigeration unit.

| Parameter                                      | Nitrogen cycle | Value   | Propane cycle | Value     |
|------------------------------------------------|----------------|---------|---------------|-----------|
| Cooling capacity, kW                          |                | 444.4   |               | 155.6     |
| The number of compressor stages               |                | 3       |               | 1         |
| Specific theoretical work of compression, kJ/kg|                | 133     |               | 95        |
| Specific thermal load on the compressor cooler, kJ/kg |        | 135     |               | 375       |
| Specific refrigerating capacity refrigerant, kJ/kg|            | 200     |               | 280       |
| Specific theoretical work choke, kJ/kg         |                | 125     |               | -         |
| The required mass flow rate of refrigerant in HE, kg / s | | 2.22    |               | 0.56      |
| Thermal load on the cooling heat exchanger of CM, kW |   | 444.4   |               | 155.56    |
| Required volumetric capacity CM, m³ / s        |                | 0.333   |               | 0.192     |
| Total thermal load on coolers of CM, kW        |                | 949     |               | 208       |
| Total mechanical power of compressors, kW      |                | 1302.5  |               | 73.3      |
| Total electric power of compressors, kW        |                | 1447    |               | 81.5      |
| Net mechanical power of the expander, kW       |                | 212.5   |               | -         |
| Power consumption of the unit, kW              |                | 1211    |               | 81.5      |
| Theoretical refrigeration cycle coefficient    |                | 0.47    |               | 2.95      |
| Actual refrigeration coefficient               |                | 0.37    |               | 1.91      |
| Total consumed electric power of the refrigeration unit, kW | | 1292.5  |               |           |
| Specific energy consumption, kW · h / t LNG   |                | 646.25  |               |           |

Any refrigerant with a boiling point of -30°C or more can use as a nitrogen circuit cooler in front of the expander. The most popular is carbon dioxide [17]. It is explosion-proof and has a low GWP but CO2 is inferior to propane from the thermodynamic point of view. The cooling capacity of propane is more than carbon dioxide.

5. Conclusions
Due to the proposed system (in comparison with small-scale LNG plant in the Perm region), it was possible to reduce the specific energy consumption by 23.06%, but the share of liquefied gas in this case is 100%. The proposed scheme is effectively implemented in plant, because on GDP and GCS NG liquefaction plays the role of co-production.

6. References
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