The Research of Compression Pressure Effect in System External Coolers of LNG Technological Cycle

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Abstract. As it is well known, that the demand for natural gas is growing, because it is the most environmentally friendly type of fuel. In addition to minimal environmental impact, natural gas has good operational and energy characteristics, which makes it an absolute leader in the global energy market. During liquefaction, natural gas becomes 600 times smaller in volume, which allows it to be transported by any ways over long distances. The issue of economic feasibility of transportation is decided on an individual basis. But liquefied natural gas (LNG) production is an energy-intensive process that requires significant operating costs. Therefore, the present work is devoted to the study of the effect of compression pressure on energy consumption in closed loops. The nitrogen and propane cycles are taken as an example.

1. Introduction

At present, global energy market is a tendency of demand change from coal and petroleum for natural gas. Mainly, this is caused by low ecological impact of natural gas as opposed to another fossil fuels. Therefore, a lot of industries are actively used NG [1]. Its transportation for consumers is basically done two ways – by pipeline and by marine LNG carriers (gas in liquid form). The last one is used in cases when pipeline are impractical and uneconomical [2,3].

LNG production is difficult process because it is required to cool gas to −161.5°C at atmospheric pressure. For the purpose of providing to this temperature, the special technological LNG schemes are being developed. These commonly involve several closed loops with refrigerants. One of them cools the other, and then natural gas gives it heat in the heat exchanger. As a result of this process gas liquefy. Efficiency of this system is estimated by operational costs. These expenses include energy consumption of cooling refrigerants. In the study we suggest estimating energy consumptions of nitrogen (R728) and propane (R290) cycle which we use like refrigerants. The i-lgp thermodynamic diagrams for the respective refrigerants and methodology for calculating refrigeration cycles are used [4].

2. The LNG process

In the last researches [5,6] are obtained that the nitrogen cycle is the most effective among another external cooling circuits for natural gas. This cycle is difficult to realize but it allows to achieve 100% of LNG outlet [7,8]. Due to limitation of expander capabilities it was decided to cool nitrogen before
expander. As a result of it allows to get -165°C of R728 after expander. Propane circuit is introduced for this purpose [9].

Figure 1 shows the proposed scheme of LNG process.

![Figure 1](image)

Figure 1. The proposed scheme of LNG process: CM – compressor; HE – heat exchanger; AC – air cooler; Exp – expander; NG – natural gas.

3. The nitrogen cycle

We refer to diagram i-lgp for nitrogen (R728) in order to estimate the possibility of plotting of the cycle and reasonability of it. Figure 2 shows this diagram.

![Figure 2](image)

Figure 2. N2 refrigeration cycle in i-lgP coordinates: 1-2, 3-4, 5-6 - compression of N2; 2-3, 4-5, 6-7 - cooling N2 AC; 7-8 or 7-8’ - cooling N2 circuit C3H8; 8-9 or 8’-9’- expansion of N2 in the Exp; 9-1 or 9’-1- cooling of the NG with a nitrogen circuit.

LNG boils at slightly above −161.5°C, therefore nitrogen should be cooled to -165°C. It is necessary due to underrecovery of heat in the heat exchanger. The inlet and outlet pressure can be adjusted but should be considered that after expansion of the nitrogen in the expander it must be reached the required temperature [4].

Pay attention to the isotherm -165 °C - it passes through vapor-liquid area. Therefore, the pressure in the heat exchanger should not be more than 14 bar. Considering that thermodynamic processes are very unstable in real-world conditions, it is necessary to set this value below [10]. Therefore, the value of this parameter will be taken based on the operating parameters of the expander.
We can set temperature before compressor ourselves (to be accepted equaling 0 °C). After each compressor we install air coolers which reduce nitrogen temperature to 30 °C. That is impossible to reach such low temperatures by throttling, therefore it was decided to use an expander. On the i-lgp diagram, the expansion in the expander is always isentropic, which is obvious advantage over the throttle. However, among the produced expanders, we were able to find only one which is in agreement to the thermodynamic parameters of the nitrogen cycle – DPV4,2-200/6-2. Table 1 shows the characteristics of this expander [11].

| Characteristic                        | Value    |
|---------------------------------------|----------|
| Refrigerating capacity, W             | 9000     |
| Regulation of efficiency, %           | 100-70   |
| Inlet pressure, MPa                   | 20       |
| Outlet pressure, MPa                  | 1        |
| Thermal gradient, °C                  | 139      |
| Coefficient of efficiency, %          | 68       |

The compression pressure is 20 MPa (see table 1) and the pressure behind the expander is 0.5 MPa. Determine the number of compressor stages in the cycle, taking into account conditions (1) and (3):

\[ \frac{P_k}{P_0} \leq 8 \] (1)

where

- \( P_k \) - pressure before compressor, MPa;
- \( P_0 \) - pressure after compressor, MPa.

\[ \frac{20}{0.5} = 40 > 8 \]

Therefore, it is necessary to determine the intermediate pressure:

\[ P_{int} = \sqrt{P_k \cdot P_0} \] (2)

\[ P_{int} = \sqrt{20 \cdot 0.5} = 3.16 \text{ MPa}. \]

Therefore, 2 stages are required. In addition, the temperature after the compressor should not be more than 170 °C.

Figure 2 shows a cycle with 2 compressor stages. The discharge temperature both after the first and after the second stage significantly exceeds the permissible (170 °C):

\[ T_{CM} < 170 \] (3)

where

- \( T_{CM} \) - temperature after the compressor, °C.

If we have two compression stages, the discharge temperature both after the first and the second stage significantly exceeds the permissible (170 °C). This means that it is necessary to generate compression with the addition of one more stage (see figure 3).

The main disadvantage of the expanders is that when changing the thermodynamic parameters of the system, we can no longer apply the model used earlier. It is all about the specifics of operation of this expansion device. If the final compression pressure is reduced, we will be able to apply an expander whose temperature difference will be less than 139 °C, which is not enough for our system.

On the other hand, it is possible to increase the cooling capacity of a nitrogen refrigeration unit by shifting line 7-8 to 8’ (see figure 2). This is achieved by deeper cooling of nitrogen in front of the expander with a propane circuit. But, in our case, doing this is unprofitable, because line 8’-9’ will cross the vapor-liquid region, which is unacceptable for expanders of this type. Alternatively, we can install a vapor-liquid expander, but it will cost more, and the process will be complicated due to the appearance of another phase - liquid.
3.1. Chapter conclusions
Unfortunately, during the study, we concluded that in our case, it is irrational to optimize the nitrogen cycle with this scheme:

- we cannot reduce the compression pressure, because the temperature gradient of expander becomes less [12];
- it is impossible to reduce the number of compression stages, because compressors have a temperature limit of operation (usually not more than 170 °C) [13]. For the same reason, you cannot increase the temperature in front of the first compressor;
- it is irrational to cool nitrogen before the expander. The inhibitory factor in this case is two-phase [14].

4. Propane cycle
To study the energy efficiency of a propane refrigeration unit, we turn to the i-logp diagram for propane (R290) (Figure 3).

![Figure 3. Propane cycle in i-logP coordinates: 1-2-3-4-5-6 - propane cycle at a compression pressure of 50 bar, 1-2'-3'-4'-5'-6' - propane cycle at a compression pressure of 30 bar, 1-2''-3''-4''-5''-6'' - propane cycle at a compression pressure of 11.5 bar.](image)

We need a propane cycle to cool the nitrogen before the expander [15]. It means that nitrogen must be cooled to -26 °C, because the temperature gradient in the expander is 139 °C. Because of the under-recovery in the heat exchanger, it is necessary to cool the propane as a minimum of -30 °C.

The diagram for propane is different: here we approximately intersect the vapor-liquid curve, therefore it is unprofitable to use the expander [16]. As a result, a throttle will be applied. During throttling, the process is depicted on the diagram in the form of a perpendicular from the compression pressure to the inlet pressure [17].

The pressure at a temperature of -30 °C is fractional during throttling, so it will be difficult to choose a compressor. It was decided to take pressure in front of the compressor 1 bar. Then, if the throttling is carried out in the vapor-liquid region, the temperature after the throttle will become -42 °C. Cooling after each compressor will be performed using air cooler also up to +30 °C.

Next, the compression pressure is needed to select. As an example, we will consider several options and see how the compression pressure will affect the number of compressor stages, cooling capacity and energy consumption.

The construction was carried out at a compression pressures of 50, 30 and 11.5 bar (see figure 3). During the study, it turned out that pressure less than 11.5 bar should not be taken, because after cooling, the AC section 4-5 will not reach the condensation line, thereby the refrigerating capacity will take a negative value, and this cycle will not make sense (see figure 4).
Figure 4. Schematic representation of propane behavior in the i-1gp diagram at a final compression pressure of 10: 1-2, 3-4 - propane compression, 2-3, 4-5 - propane cooling by air cooler, 5-6 - propane throttling.

As a result of the research, the ratio of the outlet compression pressure to the inlet compression pressure will not always fulfill the condition (1), so in all cases there will be 2 stages of the compressor.

Table 2 shows the different propane cycle parameters depending on the compression pressure are demonstrated.

| $P_k$, bar | $P_0$, bar | $P_{int}$, bar | Compressor stage number | $T_0$, °C | $T_1$, °C | $T_2$, °C | $T_A$, °C | $L_1$, kJ | $L_2$, kJ | $L_{1+2}$, kJ | $T_A$, °C | $q$, kW |
|-----------|-----------|-------------|----------------|---------|---------|---------|---------|--------|--------|-------------|---------|------|
| 50        | 1         | 7           | 2               | 0       | 85      | 130     | 30      | 120    | 105    | 225        | 30      | 337 |
| 30        | 1         | 5           | 2               | 0       | 70      | 115     | 30      | 80     | 110    | 190        | 30      | 336 |
| 11.5      | 1         | 4           | 2               | 0       | 65      | 75      | 30      | 65     | 70     | 135        | 30      | 335 |

$P_0$, $P_{int}$, $P_k$ - initial, intermediate and final compression pressure
$T_0$ - temperature before the first compressor
$T_1$, $T_2$ - temperature after the second and after the third compressor
$T_A$ - temperature after the air cooler
$L_1$ and $L_2$ - specific theoretical compression work of the 1st and 2nd stage
$L_{1+2}$ - total theoretical compression work
$q$ - specific cooling capacity of propane

According to the table we can conclude:
- if thermobaric conditions are unchanging, the number of compressor stages are unchanging in the range of the final pressure from 11.5 to 50 bar;
- the thermal capacity on the compressors and the final compression pressure decrease together, therefore the capacity on the air coolers also decreases [18];
- the lower the final compression pressure, the less compression work;
- the cooling capacity is almost unchanged under these conditions.

5. Conclusions
In this work, we investigated options for optimizing the LNG technological scheme by changing the parameters in the nitrogen and propane cycles. It turned out that under these conditions, the nitrogen cycle can have only 1 option: $P_0 = 5$ bar, $P_k = 200$ bar, the use of an expander with a temperature gradient of 139 °C, pre-cooling with an external cooler (in our case propane) to -26 °C.
When the propane circuit was studied, it turned out that the minimum possible and the most optimal compression pressure is 11.5 bar. In this case the refrigerating capacity practically does not change, and it makes no sense to spend a large amount of energy on compression.

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