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Analysis of the Possibility of Improving the Energy Efficiency of the LNG Shipment System from Large-Capacity Storage Facilities by Upgrading the Design of the Submersible Pump

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Abstract. The purpose of the research is to determine the most relevant way to improve the energy efficiency of the liquefied natural gas (LNG) shipment system from large-capacity storage facilities. The analysis of existing LNG shipment systems from storage tanks is carried out to identify critical (emergency) elements of the system that are subject to modernization, and possible options for upgrading structural elements. The work of the LNG shipment system from storage tanks is analysed, the main characteristics of the system are described. Based on the study, a method for improving the energy efficiency of the shipment system was determined – modernization of the design of the LNG submersible pump (LNGSP). The main types of submersible pumps for LNG, as well as types of drives, were studied in order to choose the most optimal option for upgrading CNG shipping systems. The replacement of the electric drive with a hydraulic turbine as part of the LNGSP was chosen as an upgrade. The possible modes of operation of the pumping unit after modernization are analysed. A mathematical description of the main operating modes has been compiled. In the future, it is necessary to calculate the hydraulic turbine in order to determine its geometric parameters.

1. Introduction

The Russian Federation is actively developing the sphere of LNG production, transportation and sale. This is associated with setting technological tasks that were solved by the LNG exporting countries 20 years ago. The reason for the chronological lag of the Russian Federation from LNG suppliers was the presence of a large land border, which allows supplying a large number of consumers with pipeline natural gas.

The analysis of existing projects of large-capacity LNG plants operated, under construction and designed (Sakhalin-2, Yamal LNG, Far Eastern LNG, Vladivostok-LNG, Pechora LNG, Baltic LNG projects) determines the specific cost of the LNG plant in the range from \$ 1200 to \$ 1600 per ton of products. With the accumulation of construction and technological experience in construction, the unit cost of LNG plants decreases mainly due to [1]:

- Increasing the capacity of technological lines for liquefying natural gas;
- Increasing the production of powerful gas turbines and superchargers.

In the LNG market, Russia is in the role of a country "catching up" with countries that have been working on the LNG market for a long time. Certain advantages can be derived from this provision,



namely, the study of technological errors will significantly save time and material resources. Generalization and adaptation of LNG production experience will allow creating competitive technologies based on the use of domestic components aimed at solving specific problems existing in the industry.

Russian economists mainly operate with unit costs per ton of LNG, which also seem to be quite significant [2]. The high cost of LNG transportation by sea vessels significantly affects the organization of transportation. The idle time of the vessel, including loading and unloading of tanks, should not exceed 24 hours. This means that by the time the methane carrier arrives in the storage, it is necessary to accumulate up to 200 thousand m³ of LNG. For plants with a capacity of about 10 million tons of LNG per year, the daily capacity is about 6.5 thousand m³, i.e. delivery of products in the amount of 200 thousand m³ is possible every 3-4 days. For this purpose, the plant has 4 storages with a volume of 40-45 thousand m³ each. Such storage facilities have enormous dimensions: a diameter of up to 80 m, a height of up to 50 m. These structures have no analogues in other areas of cryogenic technology.

Today's market of liquefied gas storage and transportation tanks is very diverse. The most popular tanks are of the membrane type. In all cases, with the exception of storage in mining recesses, submersible centrifugal pumps are used for LNG shipment, capable of pumping up to 90-95% of liquefied gas from the storage [3].

2. Relevance of the study

By analyzing the existing designs of CNG, as well as the main problems associated with their operation in the conditions of LNG shipment and accumulation, it is possible to determine the possibility of making fundamental changes to the pump design, which can subsequently contribute to the elimination of existing operational disadvantages of CNG and be used in the production of domestic units.

Based on the operational characteristics of existing brands of submersible pumps for LNG shipment, the main type of these pumps is an electrically driven centrifugal pump. However, the presence of an electric drive significantly increases the accident rate of the system, the pumps require a complete revision and in case of a breakdown or failure are not subject to repair and require complete decommissioning. In addition, most of them use rolling bearings, which also increases the system's accident rate and significantly reduces its maintainability [4].

It should be noted that when the unit and the pump are immersed in a cryogenic liquid, the inevitable problems with the shaft seal and leaks of the pumped liquid are largely eliminated, since the entire unit is in a cryogenic tank. This circumstance greatly simplifies the operation of submersible pumps.

Since the pumps are not repairable, 2-3 reserve pumps are installed in the tanks for use in emergency situations. The estimated drive power of a pump unit of one capacity is about 300 kW. Taking into account the fact that the efficiency of the centrifugal pump is 70%, 30% of the power of the LNGSP drive in the form of heat is released into the LNG storage tank. Due to the supply of heat released in the CNG during shipment, up to 30 tons of LNG are spent to compensate for these heat flows.

The use of an electric motor as a LNGSP drive creates a number of additional problems [5]:

- The problem of lubrication of rubbing parts;
- The problem of supplying electricity to the LNG layer to a depth of up to 50 meters;
- Low resistance of paint and varnish materials, wires to cryogenic temperatures, etc.

Thus, the assumption is confirmed that the pumps are the most complex and unreliable node of the LNG storage and shipment system in operation, which encourages the desire to find alternative solutions that would increase the reliability and energy efficiency of this element at the LNG plant.

The LNG stream that has passed through the turbine is discharged into the LNG storage tank in the tanker. The use of LNG as a source of mechanical energy greatly simplifies the design of LNGSP.

Bearing sealing problems are eliminated, since the flow of liquid from the turbine to the impeller does not affect the pump performance.

3. Problem statement

To solve the problem of modernization of the LNGSP design, it is necessary to perform the following works:

- Study the operating conditions of submersible pumps in LNG storage facilities;
- Assess the compliance of all types of pumps with these conditions;
- Analyse the principles that reduce the reliability of the pumps;
- Analyse the energy efficiency of LNGSP.

To analyze the scheme of LNG production from natural gas at a pressure of 5 MPa, we use the project of the Baltic LNG plant described in detail in the literature. The plant has two technological gas delivery lines, each of which produces 5×10^6 tons of LNG per year, the consumption of LNG in the delivery line to the tank is 320 kg/s. LNG is shipped to tankers periodically. For the accumulation and storage of products, the Baltic LNG plant includes four storage tanks for LNG, with a volume of 42,000 m³ each [6].

The analysis of the characteristics, advantages and disadvantages of various types of pumps based on the data of scientific and technical literature has shown that the most optimal for use as a pump in conditions of working with LNG is a centrifugal pump. Considering that about 95% of all used submersible pumps today have a centrifugal pump impeller as a working body, and also due to the lack of an alternative among other types of pump according to the aggregate of satisfactory values of the determining characteristics, it is not possible to consider the possibility of changing the type of pump in the design of the LNGSP. The use of alternative types of impellers can lead to a decrease in the overall efficiency of the system, the occurrence of additional emergencies and an increase in operating costs.

Taking into account the lack of options for replacing the impeller in the composition of the LNGSP with an alternative to the centrifugal one, the efficiency of the system can be improved by replacing the electric drive. Centrifugal pumps use electric, hydraulic, pneumatic, and mechanical drives [6]. An insufficiently studied option for using a hydraulic drive as a drive for an LNG submersible pump remains. The use of a hydraulic drive for submersible pumps will eliminate a high accident rate, the need to use bearings, and also ensure the use of LNG pumped from the tanker as a working fluid. Thus, as an upgrade of the LNGSP design, we will replace the electric drive with a hydraulic one.

In addition, the technological scheme of LNG (figures 1, 2) production already contains a hidden source of potential energy that can be used to drive CNG. The main gas enters the liquefaction unit with a pressure of 6.5 MPa, and the LNG production stream leaves the unit with the same pressure. The LNG flow is directed to a hydraulic turbine ("liquid expander"), which converts the potential energy into electrical energy and reduces the pressure of the LNG flow to a level close to atmospheric. Before the hydro turbine, LNG is in an underheated state, and its properties are similar to those of any traditional liquid [7]. If a part of this flow is directed to a hydraulic turbine coaxially placed with the LNGSP impeller, the energy of the liquid flow is converted into the energy of rotation of the turbine impeller and will be spent on the rotation of the pump impeller.

4. Description of the work of the modernized pump design

The liquid flow is taken through a control valve into an additional line that runs parallel to the main line for supplying liquid to a cryogenic storage tank (container) and is in one isolation with it, which reduces the heat supply to this additional technological flow. Accordingly, LNG enters the pumping unit in an underheated state, i.e. its properties correspond to the properties of a traditional liquid (water). If this flow is applied to a hydraulic turbine coaxially placed with the LNGSP, all the energy of the liquid flow will be converted into the energy of rotation of the turbine impeller and, accordingly, into the energy of rotation of the pump impeller. After pressure relief, the LNG flow can be directed either to the storage tank or to the LNG delivery pipeline to the tanker [8, 9]. The hydraulic

drive is controlled by a shut-off valve. The use of LNG as a working fluid will eliminate the problems of sealing bearings, since the flow of liquid from the drive side to the discharge side does not worsen the operation of the pump.

The undoubted advantage of such a scheme is that the driving and feeding fluids are one and the same substance, which eliminates the problems of sealing between the expansion part of the turbine and the discharge part of the pump. Moreover, the pump bearings can also work using LNG itself as a lubricant.

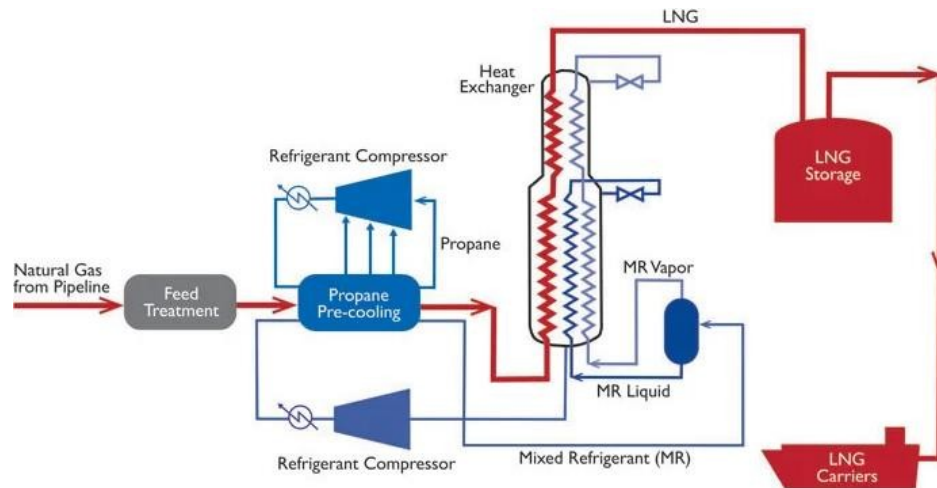


Figure 1. The LNG production stream.

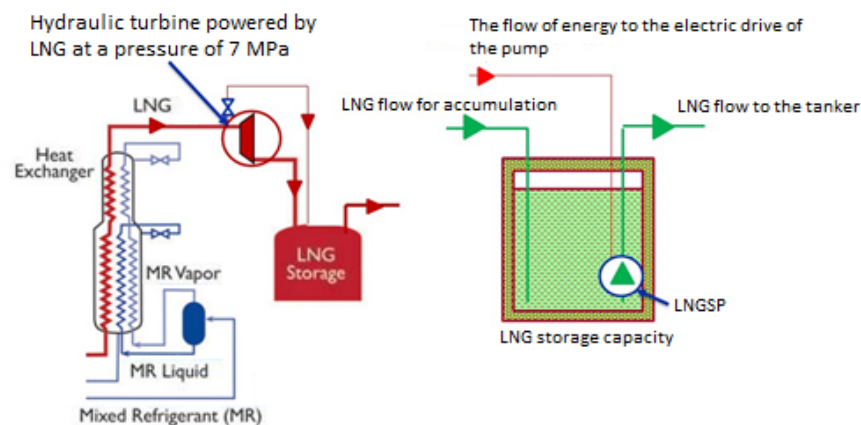


Figure 2. Hydraulic turbine for the LNGSP electric drive.

It is also worth noting that one of the advantages of using a hydraulic turbine as a LNGSP drive is that the mechanical work performed by the liquid over the wheel is transmitted to the pump wheel and there are no energy losses inherent in the electric motor. Accordingly, LNG losses from evaporation are reduced [10]. In addition, problems associated with the supply of electricity through the LNG layer are excluded.

To assess the performance of the LNGSP unit driven by a hydraulic turbine, it is necessary to make a mathematical model of the operation of the hydraulic turbine impeller in the conditions of LNG shipment from a large-capacity storage tank.

The energy spent on displacing a unit of LNG mass outside the storage depends on the fullness of the tank. The level of LNG in the storage is a function of time. The equation for calculating the displacement energy of LNG is as follows:

$$E = g \cdot (Y_{max} - y_{LNG}), \quad y_{LNG} = f(\tau) \quad (1)$$

where Y_{max} – the maximum height of the tank, $Y_{max} = 27 \text{ m}$; y_{LNG} – the level of LNG from the tank at each moment of time.

The process of LNG shipment from the storage tank can be carried out in two ways:

- With a constant flow of high-pressure LNG on the impeller of the hydraulic turbine and a variable flow in the delivery line;
- With a constant flow rate in the delivery line and a variable flow rate of high-pressure LNG on the turbine.

In the case of a constant flow of high-pressure LNG at the turbine, the full power of the turbine depends solely on the level of LNG in the storage at a given time. The increment of the turbine power is determined by the increment of the difference in the LNG levels "before" and "after" the movement of the LNG mass into the delivery line.

The constant flow of high-pressure LNG at the turbine leads to a variable flow rate in the delivery line. Changes in the LNG level equally affect the change in both the turbine power and the pump power. At the same time, the full power of the pump depends on the value of the output flow at a given time.

The system of equations describing the operating mode of the hydraulic drive unit for the first operation option has the following form:

$$\begin{cases} m_{typ} = const \\ N_{tur} = m_{tur} \cdot N_{tur}^{sp} = \frac{m_{tur} \cdot g}{\eta_p \cdot \eta_{typ}} \cdot \frac{\delta y_{LNG}}{\delta \tau} \\ N_p = \eta_p \cdot N_{tur} = \frac{m_{tur} \cdot g}{\eta_{tur}} \cdot \frac{\delta y_{LNG}}{\delta \tau} \\ m_p = \frac{N_p}{\rho \cdot g \cdot y_p}, \quad y_p - \text{pump head} \end{cases} \quad (2)$$

In the case of using the operating mode of a pumping unit with a variable flow rate of high pressure on the turbine, the LNG delivery line operates in the nominal mode at a constant mode. The power developed by the pump during operation is a function of the level of LNG in the storage tank.

During the shipment process, the amount of potential energy that must be transferred to the LNG mass to move to the delivery line increases, therefore, the power consumed by the pump increases over time. The high-pressure LNG flow rate through the turbine impeller should be regulated in such a way that, taking into account the efficiency of the component elements of the unit, the necessary power is provided on the pump shaft, and the flow rate in the delivery line remains constant throughout the entire shipment process.

The system of equations describing the operating mode of the hydraulic drive unit for the second operation option has the following form:

$$\begin{cases} m_p = const \\ N_p = m_p \cdot N_{tur}^{sp} = \frac{m_p \cdot g}{\eta_p} \cdot \frac{\delta y_{LNG}}{\delta \tau} \\ N_{tur} = \frac{N_p}{\eta_{tur}} = \frac{m_p \cdot g}{\eta_{tur} \cdot \eta_{tur}} \cdot \frac{\delta y_{LNG}}{\delta \tau} \\ m_{tur} = \frac{N_p}{\rho \cdot g \cdot Y_{tur}}, \text{ где } Y_{tur} - \text{head in the LNG supply line to the tank} \end{cases} \quad (3)$$

5. Conclusion

This article discusses the main problems associated with the design and construction of submersible pumps, the goals and objectives of the development of new designs of submersible pumps. The main types and types of submersible pumps for LNG, their varieties, as well as types of drives were studied in order to choose the most optimal new option for upgrading submersible pumps for LNG shipment systems from tankers. According to the results of the analysis, the most optimal for further development is the complete set of centrifugal submersible pumps with a hydraulic drive that allows using LNG as a working fluid. The use of a hydraulic drive in the design of the LNGSP eliminates the occurrence of additional operating costs, and also allows you to use the energy source already available in the circuit.

The upgraded design is capable of operating in two modes when shipping LNG. The main systems of the equation describing the main parameters of the unit operation (power, flow rate) during LNG shipment are obtained. With the help of the obtained systems of equations, it is possible to calculate the main characteristics of the two operating modes of the upgraded pumping unit during the LNG shipment from the storage unit.

After verification, it is planned to complicate the mathematical description of the processes occurring in the LNGSP and proceed to the study of the operation of a hydraulic drive with a variable flow rate of high-pressure LNG.

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