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Chair of Petroleum and Geothermal Energy Recovery

Master's Thesis

Development of Complex Gas Treatment Facility Technology for Field Gas Motor Fuel of Low-Tonnage Production

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Kurzfassung

Hohe internationale Standards in Bezug auf Ökologie, Sicherheit und Zuverlässigkeit, denen der modernisierte Fahrzeugpark in Russland entsprechen muss, erhöhen die Bedeutung eines zunehmenden Einsatzes von Kraftstoff für Gasmotoren. In Bezug auf das Volumen der verfügbaren Reserven und die Selbstkosten für den Endverbraucher hat der Kraftstoff für Gasmotoren eine Reihe von Vorteilen gegenüber herkömmlichem Kraftstoff. Seit 2013 wird in Russland ein Marktentwicklungsprogramm für Kraftstoffe für Gasmotoren durchgeführt. Heute gibt es ehrgeizige Prognosen für den Verbrauch und die Produktion in den kommenden Jahren.

In dieser Masterarbeit wird der aktuelle Stand des Marktes der Kraftstoffe für Gasmotoren unter dem Gesichtspunkt der wirtschaftlichen, sozialen und ökologischen Aspekte der Verwendung vom Kraftstoff für Gasmotoren sowie der staatlichen Voraussetzungen für den Übergang zum Kraftstoff für Gasmotoren analysiert und die wichtigsten Verflüssigungstechnologien für die Produktion mit geringer Tonnage vorgestellt.

Es wird auch vorgeschlagen, eine der in der Produktion mit geringer Tonnage verwendeten Verflüssigungstechnologien, ihre Nachteile und Anwendungsoptionen zur maximalen Freisetzung des Kältepotentials zu betrachten. Dies erfolgt mithilfe der Simulationsumgebung Aspen HYSYS. Eine vielversprechende Option ist die Implementierung einer Verflüssigungsanlage nach der komplexen Gasaufbereitungsanlage. Gas wird aus der ersten Separationsstufe entnommen, und mit Hilfe der Fraktionierung werden zwei Arten vom Kraftstoff für Gasmotoren erhalten.

Im Laufe der Arbeit wurde deutlich, dass es eine Reihe von Hindernissen gibt, die die Entwicklung des Marktes der Kraftstoffe für Gasmotoren behindern. Die Haupthindernisse für die Umstellung von Fahrzeugen auf den Kraftstoff für Gasmotoren sind mit einer unvollständigen gesetzlichen Regelung und einer unterentwickelten Infrastruktur von Erdgastankstellen verbunden. Ohne staatliche Unterstützung scheint die Entwicklung der Branche schwierig zu sein.

Die in Fallstudien erhaltenen Ergebnisse zeigen die mögliche Nutzung des vollen Kältepotenzials der Anlage nach der komplexen Gasaufbereitungsanlage. Mit dieser Lösung kann man zwei Arten von Kraftstoff mit einfachen physikalischen Methoden erhalten und Produkte sofort auf dem Markt verkaufen. Eine ungefähre wirtschaftliche Bewertung dieser Lösung zeigt, dass zwei Jahre ausreichen werden, um die Kosten für zusätzliche Ausrüstung zu decken.

Die Relevanz dieser These liegt in der Tatsache, dass trotz der nachgewiesenen Vorteile vom Kraftstoff für Gasmotoren, ein großer Teil der Autos immer noch mit herkömmlichem Kraftstoff betrieben wird, während die Verfügbarkeit von Ressourcen und eine fortgeschrittene technische Basis die Umstellung auf Kraftstoff für Gasmotoren ermöglichen.

Abstract

High international standards of ecology, safety and reliability that a modernized fleet of vehicles must meet in Russia increases the importance of growing use of gas motor fuel. In terms of available reserves, technology development and cost for consumers, gas motor fuel has a number of advantages over traditional fuel. Russia has been implementing a program for developing its gas motor fuel market since 2013 and currently has ambitious forecasts for its consumption and production in the coming years.

First part of this thesis analyzes current gas motor fuel market situation from the economic, social and environmental point of view. Legislative background for the transition to gas motor fuel is also considered. As for technologies, the analysis of this thesis is based on small-scale LNG production so it provides the main technologies for gas liquefaction.

It is also proposed to consider one of the liquefaction technologies, its disadvantages and application options for maximizing its free cold potential (energy that is might be transferred to the low-temperature gas stream and used for cooling the feed gas at the early stages, hereinafter referred to as free cold). A promising option is to utilize a liquefaction unit after a complex gas treatment unit. Natural gas is taken from a certain stage of separation, and two types of motor fuel are obtained by fractionation and conventional liquefaction. This is all done by means of Aspen HYSYS simulation environment.

As a result of the gas motor fuel market analysis, it came out that despite favorable conditions for its development, there are a number of difficulties that hinder its progress. The main obstacles to transfer of vehicles to gas motor fuel are related to imperfect legal regulations and poor infrastructure of gas stations. Without governmental support, the development of the industry is difficult.

The results obtained in the case study indicate that it is possible to get the most out of free cold of the liquefaction plant after a complex gas treatment unit. This solution allows producing two types of motor fuel by means of simple physical methods, as well as immediately sell products on the market. Estimated economic evaluation of this decision shows that two years will be enough to recover the expenses for additional equipment.

The relevance of this thesis consists in the fact that despite the proven benefits of gas motor fuel, the lion’s share of vehicles still run on traditional fuel. Meanwhile, there are available resources and advanced technology base that will make it possible to replace traditional fuel with gas motor fuel.

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1 Introduction

1.1 Overview

Nowadays, according to a combination of factors, gas motor fuel (GMF) is the most promising substitute for gasoline or diesel fuel especially for regions that have oil, gas and condensate fields with a high gas-oil ratio (GOR) or the presence of a gas processing plant nearby. This is due to the lower cost, as well as the lower price of switching to it in comparison with other types of fuel. In other words, the cost of developing a GMF infrastructure with increasing gas consumption, improving engines, and the cost minimization of negative environmental impact are more advantageous in today's market conditions and the current pricing policy compared to other types of fuel. The environmental aspect of GMF as a negative environmental impact factor is significantly lower than that of traditional gasoline or diesel fuel[1].

In addition to compressed natural gas (CNG) and liquefied petroleum gases (LPG), liquefied natural gas (LNG) is increasingly used as a motor fuel. LNG has a high energy intensity indicator, so it is effectively used in large-volume engines with high fuel consumption. When using LNG, the costs of preventive inspection and repair of mobile transport engines are reduced, which saves money from repairs and increases the duration of the maintenance-free run.

In 2019, the consumption of this type of fuel in Russia amounted to almost a billion cubic meters[2], and according to the program of the Ministry of Energy of the Russian Federation, it will grow to 11 billion cubic meters by 2030[3]. Nevertheless, there is a still critical lack of both infrastructure and motivation of vehicle owners for switching to GMF that hinder natural gas as a fuel to take a market share comparable to traditional fuel.

Since 2014, Gazprom has saved 4.8 billion rubles by replacing oil fuels with natural gas for consumption for own needs. The cost of LNG fuel is about 25-28 rubles/kg on average as of 01.03.2020[4]. At the same time, the reduction in emissions of pollutants amounted to more than

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[1] Aleksankov, A. (2019). Prospects for the Use of Gas Motor Fuel in Russia. Proceedings of the Saint Petersburg State University of Economics, 4, p. 96-99

[2] Protsenko N. (2020) Gas from the High Road, Oil Capital.
Retrieved from: https://oilcapital.ru/article/general/21-02-2020/gaz-s-bolshoy-dorogi

[3] Romashkina M. (2019) Development of the Gas Motor Fuel Market is Impossible without Government Support, Oil Capital. Retrieved from: https://oilcapital.ru/article/general/25-02-2019/razvitie-rynka-gazomotornogo-topliva-nevozmozhno-bez-gospodderzhki

[4] Gazprom CNG Filling Stations Chain (2020). Retrieved from: https://gazprom-agnks.ru/prices/

108.6 thousand tons[5]. Thus, when using GMF, the volume of harmful emissions is reduced by up to 10 times.

In conventional LNG production, the lion's share of the companies sticks to the certain technologies (e.g. C3MR) that have already proved their efficiency. However, small-scale LNG production has a wider range of liquefaction technologies. It is a very interesting area because their nature allows quick implementation of brand new technologies and capital costs reduction because it is possible to cover product market in a short period of time without developing transport infrastructure.

Innovation and technology are the most expensive parts in the LNG production-consumption chain. The choice of technology depends on the capacity of production lines and the efficiency of their operation in various climatic conditions. Much attention is paid to the choice of the refrigeration cycle, as well as the type of refrigerants used (in case of availability of refrigerant), which accordingly affects the cost of building an LNG plant in various countries and regions of the world.

1.2 Motivation

In 2019, Russia produced about 40.2 billion cubic meters of LNG. In addition, it is expected to produce 100-120 million tons of LNG by 2035[6]. Small-scale LNG will account for approximately 5.6 million tons of this quantity[7].

In case of implementation of incentive measures, the absolute potential demand for GMF by 2030 could reach more than 13 million tons in oil equivalent, which will ensure the displacement of a similar volume of petroleum products: diesel fuel and gasoline.

GMF can compete with oil products on the Russian market. It will help to reduce load on refineries that are working to ensure uninterrupted supply of high-quality fuels to the domestic market, improve the environmental efficiency of the transport sector, and create additional volumes of demand for Russian gas[8].

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[5] Alfirova E. (2019). Goal-Regions. Gazprom Considered the Development of the Russian Gas Motor Fuel Market, Neftegaz.RU. Retrieved from: https://neftegaz.ru/news/gas-stations/497713-tsel-regiony-gazprom-rassmotrel-voprosy-razvitiya-rossiyskogo-rynka-gazomotornogo-topliva/

[6] The Ministry of Energy Predicts an Increase in LNG Production in Russia in 2019 by Almost 50%. Prime, Business News Agency. Retrieved from: https://1prime.ru/energy/20191227/830748508.html

[7] Ishmuratova M., Snitsky D. (2019). Russian Small-Scale LNG, Regional Series: Kuzbass, Yakutia, Far East, Sakhalin, Black Sea. Energy Center of the Moscow School of Management SKOLKOVO, p. 54

[8] Grushevenko E.V, Kapustin N.O., Ryjkova V.V. (2016). System Analysis of the Gas Motor Fuel Market Development in Russia, Environmental Bulletin of Russia, p. 4-9

Now, Gazprom gas-engine fuel has focused its efforts on creating a modern gas-refuelling infrastructure on the territory of the Russian Federation. In addition, they are implementing targeted investment projects aimed at creating gas motor transit corridors on the main Federal highways of Russia. This will be a condition for further market development with a high degree of participation of private capital and independent operators[9].

1.3 Objective

The objective of this research work is to modernize the technological scheme for small-scale LNG production as a gas motor fuel and consider application options for maximizing the use of free cold containing in the system based on the analysis of current situation of the Russian market of gas motor fuel consumers.

[9] Cheminava B.T., Kondratenko S.E. (2017). Development of the Russian Gas Motor Fuel Market by Attracting Private Investments, Gas Industry № 12, p. 74-78

2 Gas Motor Fuel Market Analysis

2.1 General Information

In Russia, in recent years, more and more attention has been paid to improving energy efficiency, rational use and saving energy. This is primarily due to the need to improve the competitiveness of the country's economy, which, despite some positive dynamics, is still characterized by high energy and carbon intensity of GDP[10].

Conversion of transport to GMF is one of the strategic directions of the state's activity, which corresponds to the following main directions of the state's policy in the socio-economic sphere:

1. Rational use of hydrocarbon raw materials and increasing utilization of the existing raw material base, in particular associated gas, because the degree of its use currently does not exceed 5 – 10%[11].
2. Reducing the cost for public, business and government fuel of motor vehicles, as GMF is cheaper compared to gasoline fuel.
3. Development of small businesses in the field of GMF.

GMF is an alternative fuel for internal combustion engines, obtained mainly from natural and associated gas. The following provide the advantages of using natural and associated gas as a GMF[12]:

1. Presence of a developed gas distribution system in Russia
2. No need for significant changes in the engine design
3. Reducing the amount of harmful exhaust gases emissions in comparison to gasoline fuel
4. Reduction of costs for the production of GMF (in comparison to oil products)

2.2 Necessary Infrastructure

In Russia, the development of the GMF market is at an initial stage. KAMAZ has achieved some success by developing a cryogenic fuel system. Already the first tests of KAMAZ vehicles in the Sverdlovsk region showed the LNG consumption cost of 4.95 rubbles per 1 km (a tank with a volume of 450 litres of LNG provides a mileage of 600 km). However, the main obstacle in converting vehicles to LNG is the linking of transport to LNG sources – LNG fuel station, which quantity is currently insufficient. A refuelling infrastructure is necessary: it should be

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[10] Ratner, S. V. (2013). Questions of Practical Realization of the State Economic Policy in the Field of Energy Efficiency. Economic Analysis: Theory and Practice

[11] Silakova, V. V. (2012). Realization of Actions for Strengthening of Ecological Safety in an Oil and Gas Complex based on Scientific and Technical Cooperation. Economic Analysis: Theory and Practice

[12] Grachev I. D., Sharapov M. M. (2014). Gas Motor Fuel as Alternative to Traditional Sources of Consumption of Engines. Economic Analysis: Theory and Practice

presented along the routes with the largest cargo and passenger traffic as well as on secondary routes[13].

LNG plants are also important infrastructure elements. To provide fuel for cars on the highway, so-called mini-factories that are built directly near the buyer are more profitable. Fuel is delivered to filling stations in special tankers, at a distance of about 100 km. The capacity of these plants reaches 20 thousand tons per year, which is 10 times less than the capacity of conventional plants, and methane coming from the gas network is enough to provide them with raw materials. In Russia, there is a manufacturer of such plants – NPF "EKIP"[14].

Gazprom gas-engine fuel is already developing an infrastructure project to create international gas motor corridors linking Europe and Asia. The project covers the territory of the European part from Kaliningrad to Yekaterinburg, that is, where there is already a network of roads and gas stations. Further expansion of the GMF market will be facilitated by the development of low-tonnage LNG production in the North-Eastern and Eastern regions of Russia[13].

Speaking of the development of the GMF market, the most interesting is small-scale LNG production, in which gas is liquefied at local installations located near the gas pipelines: gas distribution stations (GDS) and automobile gas-filling compressor stations (CNG stations). This arrangement is characterized by low initial capital investment and easy start-stop, which allows one to flexibly adjust the station's performance and adjust it to the dynamics of LNG consumption[15].

The most promising direction for the development of small-scale LNG production is the gas liquefaction technology at the GDS. Based on the use of the pressure drop between the main and distribution gas pipelines it significantly reduces the energy costs of gas liquefaction and, as a result, the production cost and cost for the final LNG consumer[16].

The development of small-scale LNG represents a great chance for the Russian gas industry. Thanks to this promising segment, it is possible not only to increase the efficiency of the

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[13] Fedorova E. B, Melnikov V. B. (2015). Prospects for Development of Small-Scale Liquefied Natural Gas in Russia. Oil & Gas Chemistry, p. 44-51

[14] Tsvetkov V. A., Zoidov K. H. New Evolutionary Model of Transport and Communication Interaction Between Russia and China

[15] Lyugay, S. V. (2010). Increasing the Efficiency of Natural Gas Liquefaction at Gas Distributing Plants at Gas Main Pipelines. In Ph.D. Thesis in Engineering Science. Moscow: Gazprom VNIIGAZ LLC

[16] Gorbachev S.P., Lyugay S. V. (2015). Problems and Prospects of LNG Production at Gas Distributing Plants. Special Issue – Gas in Engines, 728, p. 45-49

country's gas industry as a whole, but also to change the energy balance of individual regions of the country and neighbouring regions of foreign countries[17].

Small-scale LNG will primarily focuses on local markets located near the production site. LNG producers can use pricing models linked to local energy sources, thus encouraging buyers to save by switching to LNG[18].

2.3 Demand in Gas Motor Fuel

The expected increase in natural gas consumption has a stimulating effect on the GMF market. The share of natural gas in developed countries increases based on the energy balance, taking into account such components as environmental security and diversification of supplies, whereas for developing countries, gas consumption will increase due to the growing needs of the developing economy. The United States of America and South-East Asian countries such as South Korea and China are among the regions that are projected to see a significant increase in demand for GMF[12].

The potential demand for LNG was determined by sections of federal and regional highways, taking into account the traffic intensity of vehicles, the rate of consumption of diesel fuel, and the coefficient of substitution of diesel fuel for LNG.

Gazprom gas-engine fuel estimates that the potential demand for LNG as a motor fuel in Russia will be around 5.2 million tons per year by 2030. Due to the competitive advantages noted above, LNG as a fuel type is extremely attractive in the following target transport segments:

1. Highway transport (trucks with a load capacity of more than 12 tons, intercity buses) – 1.7 million tons per year
2. Water transport (ferries, container ships, bulk carriers, tankers) – 1.4 million tons per year
3. Quarry machinery (quarry dump trucks with a load capacity of more than 90 tons) – 1.2 million tons
4. Railway transport (mainline gas-turbine locomotives, shunting gas-heat locomotives) – 0.5 million tons
5. Agricultural machinery (tractors) – 0.4 million tons

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[17] Gorbachev S.P., Medvedkov I. S. (2016). Peculiarities of LNG Small-Scale Production at Gas Pipelines Based upon High-Pressure Throttle Cycles. Industrial Gases, 16, p. 29-36

[18] Nikiforov, O. (2018). Prospects for Small-scale production: Not Only Large Enterprises Are Interested in Liquefied Natural Gas. (NG-Energy) Retrieved from http://www.ng.ru/energy/2018-09-10/13_7307_spg.html

LNG can replace more than 15% of the total volume of traditional fuel consumed in these transport segments by 2030[19].

Based on the fuel and lubricants consumption standards approved by the Ministry of transport of Russia, it is possible to estimate the reduced consumption of GMF for traditional types of motor fuel as following[20]:

1. Consumption of 1 litre of gasoline corresponds to a consumption of 1.22 litres of LPG to 1 cubic meter of natural gas in normal conditions or 1.67 litres of liquefied natural gas (based on average values of the coefficient of liquefaction of natural gas 600)
2. Consumption of 1 litre of diesel fuel corresponds to the consumption of 1.53 litres of LPG, 1.25 cubic meters of natural gas under normal conditions, or 2.09 litres of liquefied natural gas

2.4 Types of Transport for Gas Motor Fuel

When using LNG, attention is drawn to the development of special cryogenic process equipment and fittings, as well as auto and railway tanks for its transportation, the creation of basic low-temperature storage of large volume and small-capacity transfer storage at gas filling stations.

In comparison with compressed gas, LNG provides greater mileage and load capacity, since its density is higher and the pressure is lower[21].

2.4.1 Highway Transport

The success of LNG development in the Russian Federation may lie in the fact that the main volume of cargo transportation within the country with a sufficiently large area is carried out by motor transport. The share of fuel component in the cost of freight transport is very significant, and private business is trying to optimize it, especially in the context of slowing economic growth.

Installation of complex cryogenic fuel systems is most effective on powerful heavy trucks, since they account for a large share of harmful emissions. Thus, it is more promising to consider the market of heavy trucks that make federal transit transportations over a distance of more than 500 km, as well as transit buses. These vehicles make a significant daily mileage and consume

[19] Kondratenko, S. (2017). Prospects for Using Liquefied Natural Gas as a Motor Fuel in Russia. Gas Industry, 4, p. 76-82

[20] Order of the Ministry of Transport of the Russian Federation of 14.03.2008 no. AM-23-R "On the Introduction of the Guidelines" Standards of Fuel and Lubricants Consumption in Road Transport""

[21] Baikov N. M., Saifeev M. A. (1974). Production and Use of Liquefied Gases Abroad (Review of Foreign Literature). Moscow: VNIIOENG

a lot of fuel, so their transition to LNG will provide significant savings in operating costs for carriers.

From consumer characteristics point of view, LNG equipment is no longer inferior to its diesel counterparts. Recently, the company introduced the New Stralis NP truck, which is focused on international transportation, running on both CNG and LNG. This car is equipped with a 400 horsepower Euro 6 engine with a torque of 1700 N•m, equal to the diesel equivalent[22].

The number of centres for installation of gas cylinder equipment in Russia increases annually what helps private car owners to re-equip their vehicles. In addition to the possible savings when using gas, the car retains the ability to work on gasoline.

According to experts' estimations, the entire fleet of gas and dual fuel vehicles in the Russian Federation is approximately 245000 units. In fact, active accounting of gas-powered vehicles is conducted only since 2017 so this number should be larger.

The industry has prospects, but they are very limited by external conditions. If the government continues to subsidize the purchase of equipment using GMF, the construction of gas stations will develop by 2023, the fleet of GMF vehicles may grow[23].

2.4.2 Railway Transport

Switching to GMF does not apply to cars only. Active work on the development and implementation of engines working on the GMF is underway in the railway industry. Russian Railways have already purchased motive-power units working on GMF (gas turbine units) and plans to actively develop the use of GMF, especially in those regions where the appropriate infrastructure already exists. The expected total effect of using GMF can be 15-20% of current expenditures[1].

In the railway segment, LNG is promising to be used on non-electrified sections of the railway. According to Russian Railways, in comparison with a diesel motive-power units, when using a gas turbine unit, environmental damage is reduced by 2.5 times and total annual operating costs are reduced.

2.4.3 Water Transport

The relevance of using GMF on sea vessels is reasonable due to the systematic tightening of requirements for the content of sulphur oxides, nitrogen and carbon, as well as solid particles in marine emissions.

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[22] Arteconi A., Polonara F. (2016). LNG as Vehicle Fuel and the Problem of Supply: The Italian Case Study. p. 503-512

[23] No gas for gas, Russian gas community. Retrieved from https://www.gazo.ru/events/5849/

As a fuel, liquefied natural gas is used directly on LNG tankers that transport large volumes of LNG. GMF can be used in marine power plants, namely: diesel (four-stroke, two-stroke and gas), gas and steam turbines.

It is possible to use all types of tanks used on gas carriers for placing LNG reserves on a ship (membrane, plug-in tanks and prismatic plug-in tanks of the SPB type).

In January 2017, a new high-speed ferry operating regular flights from Tallinn to Helsinki was first bunkered with Russian LNG produced at the low-tonnage LNG PLANT in Pskov. The plant is built on the GDS, and in the cryogenic cycle, it partly uses the cooling effect as a result of lowering the pressure on the GDS[24].

2.4.4 Jet Fuel

The use of LNG as a jet fuel leads to an increase in useful load of the aircraft, increasing the speed and reducing operating costs.

Liquefied methane is significantly superior to jet fuel. It can be used to cool the heated metal parts of the exhaust system, which are primary sources of infrared radiation.

This makes it possible to achieve significant advantages in the technical characteristics and performance of gas turbine engines, which is typical for rocket engines that burn liquid oxygen and liquid hydrogen.

When switching to LNG as a fuel, engine noise is significantly reduced because of reducing the exhaust force of the exhaust gases[21].

2.4.5 Quarry Machinery

In accordance with Russia's position in the global mining industry, the country has a concentration of 7.8 % (approximately 2.5 thousand units) of the world's fleet of dump trucks with a load capacity of 90 tons or more.

The use of LNG as a motor fuel avoids the potential reduction in work productivity associated with severe air pollution in the quarry itself.

LNG mining equipment can be used in areas where mining companies directly extract minerals. The additional use of LNG as a motor fuel allows for uninterrupted operation of machines for a long time, as well as reducing the smoke and toxicity of exhaust gases in poorly ventilated pits.

[24] Ogorodnikov, E. (2017). There Will Be Tons of Liquefied Gas. (Expert)
Retrieved from http://expert.ru/expert/2017/06/zalyut-zhidkim-gazom/

2.4.6 Agricultural Machinery

The tractor fleet is the main consumer of motor fuel and the most promising type of equipment for the use of GMF in agriculture. For agricultural producers, the power/traction characteristics of machines used are critical.

The agricultural machinery segment is highly fragmented, both geographically and in terms of the number of equipment owners. The seasonal demand factor is clearly expressed in the segment, so the introduction of LNG in agriculture is considered when developing adjacent consumption segments (main transport, water, etc.). In agriculture, the transition from diesel to LNG will provide an absolute competitive advantage[19].

2.5 Economic Aspects for Switching to Gas Motor Fuel

Small-scale LNG projects are becoming more attractive in the face of falling oil and natural gas prices. There are several reasons for this[25]:

1. Capital investment in small-scale LNG production is significantly less than in a large-scale plant
2. Construction period of a small-scale plant is 1-3 years, while the average construction period for large-scale plants is 5 years
3. Payback period for small-scale projects is less than for large-scale ones

In contrast, the large segment of small-scale LNG is not technologically dependent: the acquisition of technology and equipment may have a large number of suppliers to optimize CAPEX and minimize sanctions risks[18].

The cost of gas on average in Russia is 50% lower than the cost of gasoline, while the energy output is almost the same. The transition to the use of GMF is beneficial not only for private car owners, but also for legal entities, due to its cost-effectiveness, which in turn leads to a significant reduction in the cost of their own, corporate or public funds[26].

According to the data announced at the St. Petersburg International Economic Forum (SPIEF) 2019 session "Gas motor fuel. Economy and climate", currently about 1.4 billion cars are used in the world, only 24 million of them are powered by GMF, about 80 countries use GMF, and about 31000 gas stations operate, including 18000 in China, India and Iran[27].

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[25] Kondratenko, A. D. Karpov A. B., Kozlov M. A. (2016). Russian Small-Scale Production of Liquefied Natural Gas. Oil and Gas, p. 31-36

[26] Makarova I. V., Khabibullin R. G., Gabsalikhova L. M., Valiev I. I. (2010). Prospects and Risks of Transport Conversion to Gas Motor Fuel. p. 1209-1214

[27] Gas Motor Fuel. Economy and climate. Information-analytical system of Recongress. (2019).

2.6 Ecological Aspect

The amount of harmful emissions into the atmosphere when using LNG is significantly less: it completely lacks solid particles and sulphur compounds, carbon monoxide and heavy hydrocarbons emissions are reduced by up to 65%, and nitrogen oxide emissions are reduced[28].

Exhaust gases account for the largest part of the harmful substances released by the internal combustion engine. Most of all, when burning motor fuel, carbon monoxide is released, which is stored in the atmosphere for about 3 – 4 months, and many other various hydrocarbons. Benzapyrene, which is a class 1 substance, is particularly dangerous. A comparison of the emission of toxic components in the exhaust gases of internal combustion engines running on gas and traditional fuel with optimal adjustment of the fuel equipment [%] is given in table 1.

Table 1: Motor Fuel Toxic Components Emission[29]

Type of motor fuel	**CO, [%]**	**C_xH_y, [%]**	**NO_x, [%]**	**Benzapyrene, [%]**
Gasoline	100	100	100	100
Gasoline (catalytic car)	25-30	10	25	50
Diesel	10	10	50-80	50
LPG	10-20	50-70	30-80	3-10

When comparing the table's indicators, we can say that cars running on LPG actually emit less harmful substances (especially benzopyrene) into the atmosphere than cars running on gasoline and diesel fuel. One can make sure that LPG-powered vehicles are the most realistic candidates for the role of environmentally friendly road transport[30].

United Nations Economic Commission for Europe (UN/ECE) Regulation No. 49 defines the requirements for GMF used in gas-powered motor vehicles. They regulate the use of reference fuels in an experimental study when obtaining "engine approval" for the level of emission of polluting gases, particulate matter, and smoke[31].

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[28] Gritsenko A. I., (1999). Collection and Field Preparation of Gas in the Northern Fields of Russia. Moscow: Nedra Moscow

[29] Zaikin, O. A. (2014). Features of the Use of Alternative Energy and Modern Gas Cylinder Systems in Road Transport. Astrakhan: State Technical University-Astrakhan: Publishing House of AGTU

[30] Mirov B. K. Ecological Efficiency of Application of Liquefied Hydrocarbon Gas in Road Transport, Current Issues of Technical Sciences. (2019). p. 45-47

[31] The UN/ECE Regulation № 49. Uniform Instructions Concerning the Certification of Vehicles with Compression-ignition Engines which with Regard to the Emission of Pollutants Operate on Natural Gas

GMF must meet high international quality standards. For LNG, these quality requirements are supplemented by requirements for the content of crystallizing components that can clog equipment during the production, pumping, storage, and regasification of LNG. The CO_2 content is specified, and its share in LNG should not exceed 50 ppm[32].

The world's cleanest production line vehicle with internal combustion is an NGV – Honda Civic GX, sold in the US. It has a specialized engine that is recorded to generate exhaust emissions in high polluting areas, which are cleaner than the air exiting the engine. The Civic will travel to East Coast from the West Coast of the United States and emit less non-methane hydrocarbons than if you spill one tablespoon of fuel[33].

2.7 Legislative Background

The future development of the GMF market depends largely on government support measures, starting from supporting and encouraging car manufacturers to use GMF and maintaining existing car prices. It also requires direct support for regions with the possible creation of specialized clusters, and diversified development of all industries where GMF can be used.

In 2018, the Russian Ministry of energy prepared a program for GMF market development until 2024, for which it is expected to be allocated 175 billion rubbles from the budget. The goals of the program are to increase the number of gas stations by four times, and gas sales by five times. Furthermore, oil and gas companies that will build new gas refuelling stations are expected to compensate 25% to 40% of expenses, based on the cost of one LNG filling station from 150 million rubbles[34].

The world’s experience shows that the measures of state support for small-scale LNG, combined with the absence of barriers to its export, allow for rapid growth in this segment and create additional incentives for the development of the LNG industry as a whole. Therefore, thanks to the development of small-scale LNG, China now has a colossal total LNG production capacity that exceeds the capacity of many major global gas producers. In the US and Canada, small-scale LNG has entered foreign markets: the US supplies LNG to the Caribbean in this way, while Canada is conducting test deliveries to China. Norway, which pursues a target to

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[32] GOST R 56021-2014. "Liquefied Natural Gas. Fuel for Internal-combustion Engine and Generating Units. Specifications".

[33] Natural Gas Vehicle Knowledge Base: Emissions. (NGV Global)
Retrieved from http://www.iangv.org/natural-gas-vehicles/emissions/

[34] The Ministry of Energy Will Add Gas: the Essence of the Program for the Development of the Gas Engine Market. (2018). (RBC)
Retrieved from https://www.rbc.ru/business/26/11/2018/5bf551d19a794705c3f0d95d

develop this segment through tax incentives and other mechanisms, has already become a world leader in the use of LNG in shipping.

An important condition for the development of the GMF market is the abolition of Gazprom's monopoly on LNG exports for small-scale production. In addition, in Siberia and the Far East, along export gas pipelines, infrastructure may eventually be created for the use of small-scale LNG in the domestic market, which is particularly promising in terms of gas supply to settlements that are not connected to a unified gas supply system, and in terms of the needs of the GMF industry[18].

Currently, the Russian Government is also interested in using GMF, developing its production and consumption market. Various state programs are adopted for these purposes:

1. Provision of state subsidies for the purchase of agricultural machines running on GMF
2. Provision of investment tax credit in case of investment in facilities and technologies for the production of passenger cars running on GMF

In addition, it is possible to adopt the Federal law "on the use of alternative types of motor fuel", which will contain additional types of state support for this type of activity[12].

2.8 World Market of Gas Motor Fuel

The growing GMF sector may make changes to the structure of global LNG trade. Twelve European countries aimed at improving their own ecology have developed the project "Blue LNG corridors" (figure 1), which began in May 2013. The project's goal is to introduce LNG as a real alternative to diesel fuel for heavy trucks. To achieve this goal, the project has defined a scheme for placing LNG refuelling points along four corridors, two of which will cover the waters of the Atlantic Ocean and the Mediterranean region, and two will connect Southern Europe to the North and Western Europe to the East. To do this, about 14 new gas stations were built in critical areas along the "Blue corridors". At the same time, about 100 heavy trucks using LNG as fuel were built[13].

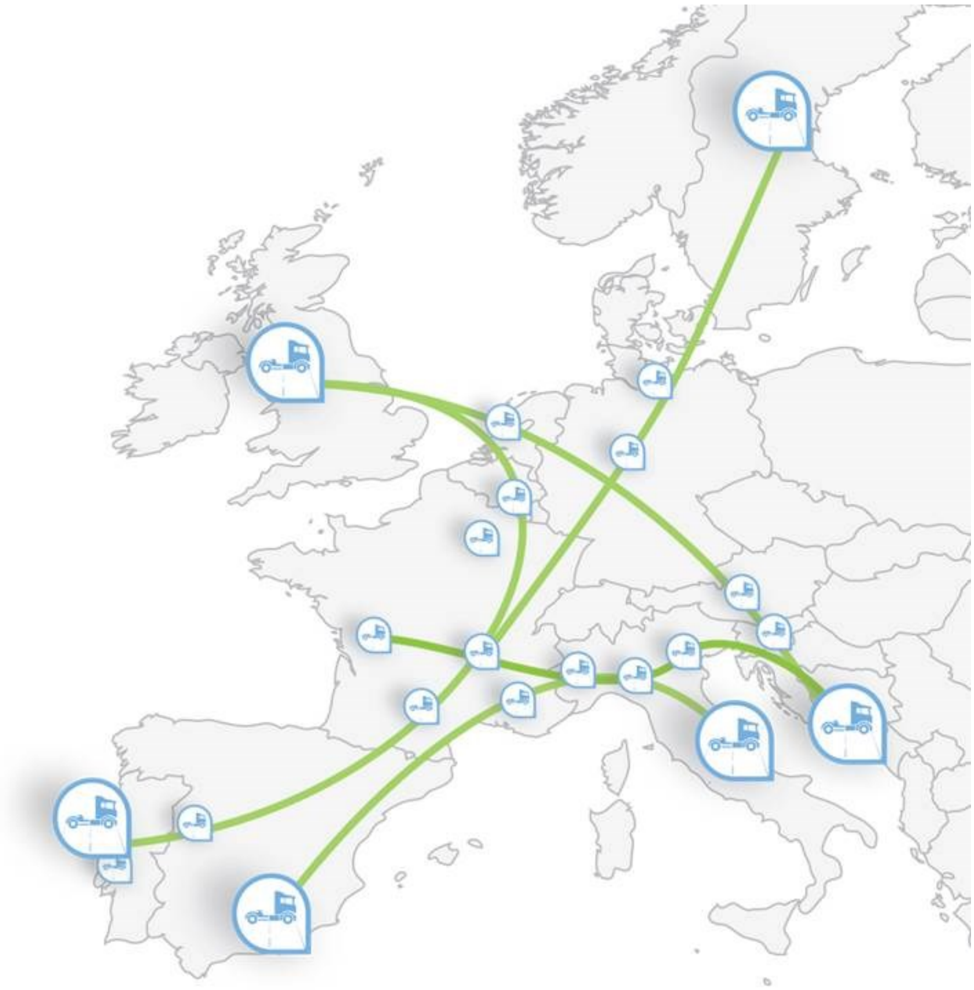

Figure 1: Map of LNG Blue Corridors[35]

At the moment, the global LNG market is developing under the influence of a number of factors that allow one to identify trends in its development in the twenty-first century, namely[36]:

1. Increasing the volume of proven natural gas reserves in the world
2. High concentration of resources in a small number of countries
3. Steady growth of LNG production capacities in the world and a high level of their workload
4. High technological level of LNG production in most exporting countries
5. Increasing the number of LNG importing countries
6. Maintaining positive dynamics of LNG production level and consumption in the world

[35] LNG Blue Corridors – Across (Parts of) Europe. Retrieved from https://gazeo.com/up-to-date/news/2014/LNG-Blue-Corridors-across-parts-of-Europe,news,8000.html

[36] Tsvigun I. V., Ershova E. V. (2016). Global LNG Market: Current Situation and Development Trends. Bulletin of Baikal State University, 26, p. 868-881

2.9 Difficulties That Hinder Introduction of LNG as a Motor Fuel

The highway transport segment is characterized by the largest potential demand for LNG, but in terms of gas filling infrastructure localization is difficult to implement, since it is distributed along federal highways of the Russian Federation with a total length of more than 50000 km.

The only acceptable option for the end consumer to create a gas filling infrastructure is construction of gas stations on the entire logistics leg.

In Russia, there are barriers that prevent the widespread introduction of LNG as a motor fuel, in particular[19]:

1. Lack of supply infrastructure for LNG as a motor fuel
2. Absence of a unified development strategy and efforts coordination
3. Imperfection of the legal and regulatory framework
4. High cost of imported technological equipment, as well as LNG vehicles
5. Lack of own serial production of LNG vehicles

Another factor that limits GMF development is a problem with actual vehicle registration system that sometimes forces owners to wait for permits for several months because of low-quality administrative services. It often happens in remote areas located far from developed cities. However, transport running on the GMF is particularly in highly demand in those areas. Changing rules and regulations of administrative control of ownership and registration of vehicles working on the GMF is necessary to promote this type of transport[1].

3 LNG Technology Analysis

LNG is a liquid multi-component mixture of light hydrocarbons, which is mainly methane. To produce LNG, natural gas is first purified from carbon dioxide and hydrogen sulphide, then dried and purified from mercury, after which the C3 fraction and heavier hydrocarbons are separated. The remaining methane gas, depending on the calorific requirements for the product, can have 3-4% ethane, 2-3% propane, up to 2% butane, and up to 1.5% nitrogen as impurities. If this mixture of methane with other gases is cooled to about -160 °C at a pressure slightly higher than atmospheric (the boiling point of pure methane at atmospheric pressure is -161.5 °C), it turns into a liquid[37].

LNG is produced from natural gas by compression followed by cooling. When liquefied, natural gas is reduced in volume by about 600 times. The liquefaction process takes place in stages. At each stage, the gas is compressed, then cooled and transferred to the next stage. The actual liquefaction occurs when cooling after the last stage of compression. The liquefaction process thus requires significant energy consumption, up to 25 % of the amount contained in the liquefied gas[38].

Various types of installations are used in the liquefaction process – throttle, turbo-expander, turbine-vortex, etc.

When considering gas liquefaction technologies, special attention is paid to refrigeration cycles, where hydrocarbon or other substances (compounds) are used to absorb heat from natural gas, which is cooled by passing through multiple expansion cycles before the LNG enters the gas turbine of a refrigeration compressor. This is the key process on which various liquefaction technologies are based.

3.1 Main Technological Processes of Natural Gas Liquefaction

In small-scale technological processes, natural gas is liquefied in two ways: by means of external refrigerant or by using the expansion of part of the natural gas flow. In the first case, one is using an external source of cooling in the form of a closed refrigeration cycles using refrigerant gas. In the second case, the working body of the refrigeration cycle is directly a stream or part of the natural gas stream, which is subjected to sequential compression, cooling and expansion in one or more stages. In this case, the refrigeration cycle is open. A

[37] Fedorova E. B. (2011). Current State and Development of the Global Liquefied Natural Gas Industry: Technologies and Equipment. Moscow: Gubkin Russian State University of Oil and Gas

[38] Liquefied Natural Gas (LNG), Liquefaction Technologies. (Neftegaz.Ru: Technical Library) Retrieved from https://neftegaz.ru/tech-library/energoresursy-toplivo/141460-szhizhennyy-prirodnyy-gaz-spg-tekhnologii-szhizheniya/

combination of two methods can also be used. Classification of small-scale LNG production processes is shown in figure 2.

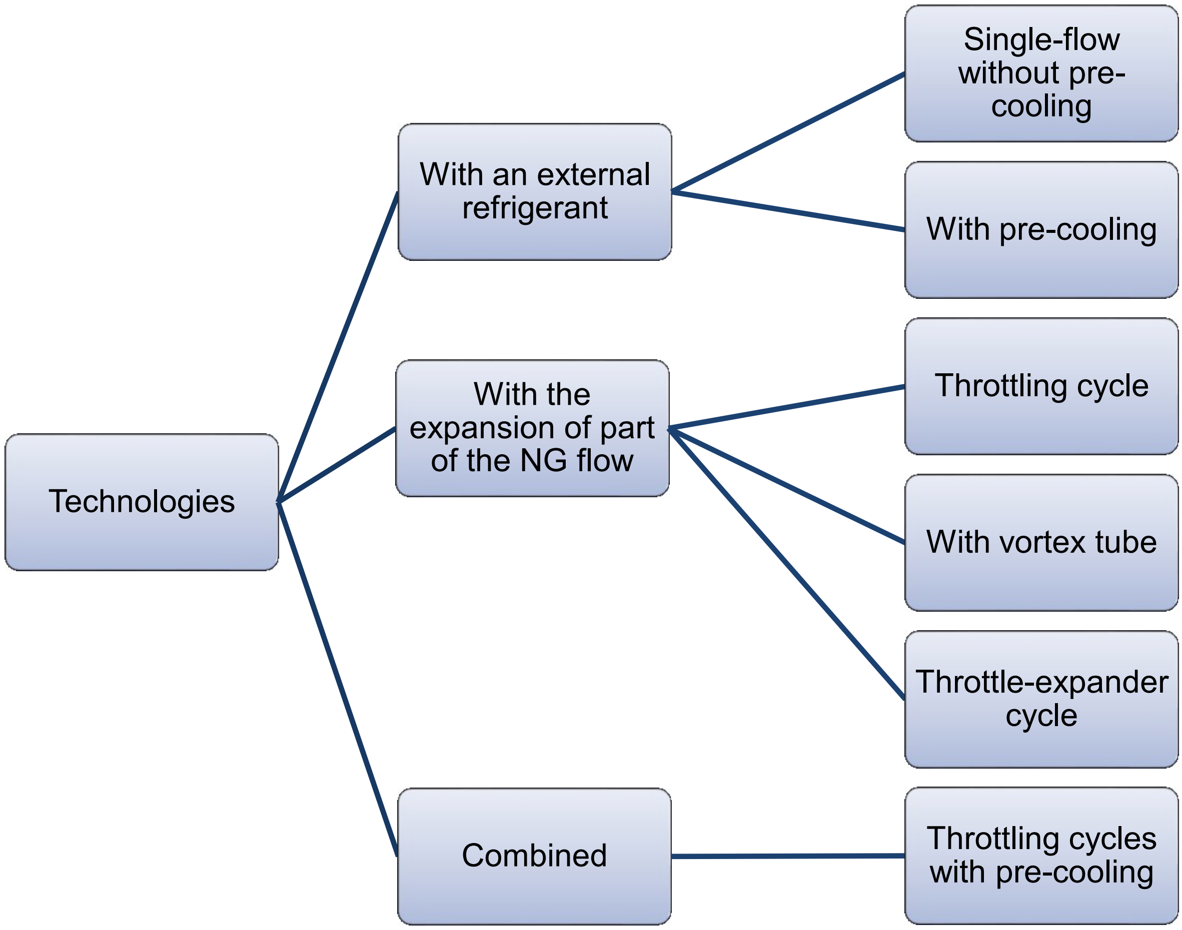

Figure 2: Classification of Small-Scale LNG Production Processes[25]

The process using refrigerants can include one or two refrigeration cycles – pre-cooling and liquefaction. As practice shows, the use of more than two refrigeration cycles in small-scale production is impractical, since simplicity and compactness in this case are the determining factor.

Two main groups of processes belong to the technological processes of natural gas liquefaction with an external refrigerant: nitrogen cycles and cycles on mixed refrigerants – mixtures of light hydrocarbons and nitrogen. These technologies dominate the productivity range from 3.5 to 35 tons of LNG per hour.

Open cycles, where the refrigerant is part of the raw gas flow, are based on the use of natural gas expansion in expanders. Efficiency and number of expanders has a direct impact on the overall efficiency of the liquefaction process[37].

3.2 Description of the Technological Processes for Natural Gas Liquefaction

3.2.1 Technological Processes for Natural Gas Liquefaction by an External Refrigerant

3.2.1.1 Nitrogen Refrigeration Cycle

Processes based on this technology are widely used in plants to cover the peak demand for natural gas.

Nitrogen refrigeration cycle with expanders is widely used due to its simplicity, safety and availability of nitrogen as a refrigerating agent. Nitrogen is obtained at air separation plants and transported in gas cylinders or tanks. There is the expander installed in an external circuit, where the working medium is nitrogen.

Feed gas is processed in the same way as in any other cooling process: the gas is drained, purified, and heavy components are removed from it.

The installation diagram is shown in figure 3. Natural gas passes through the cleaning and drying unit and passes through the heat exchanger HE-1, where it is cooled with liquid nitrogen, after which it is throttled and enters the separator, where the steam phase is separated from the LNG.

Nitrogen, having cooled the flow of natural gas in the heat exchanger HE-1, is compressed stepwise (first by the compressor C-1, and then by the compressor C-2, running on energy from the expander) and cooled after each stage. After that, part of the nitrogen enters the evaporator HE-2, where it is cooled in a refrigeration machine, and then the streams are combined. Then nitrogen passes through the heat exchanger HE-1, where it is cooled, and enters the expander. The resulting energy of the expander is used for compression at one of the stages. From the expander, liquid nitrogen flows back to the heat exchanger HE-1 to cool the natural gas flow. Compression heat is removed by conventional water cooling.

It should be noted that the liquefaction coefficient on this unit is close to 0.99. Estimated specific energy costs are 840 kWh/ton.

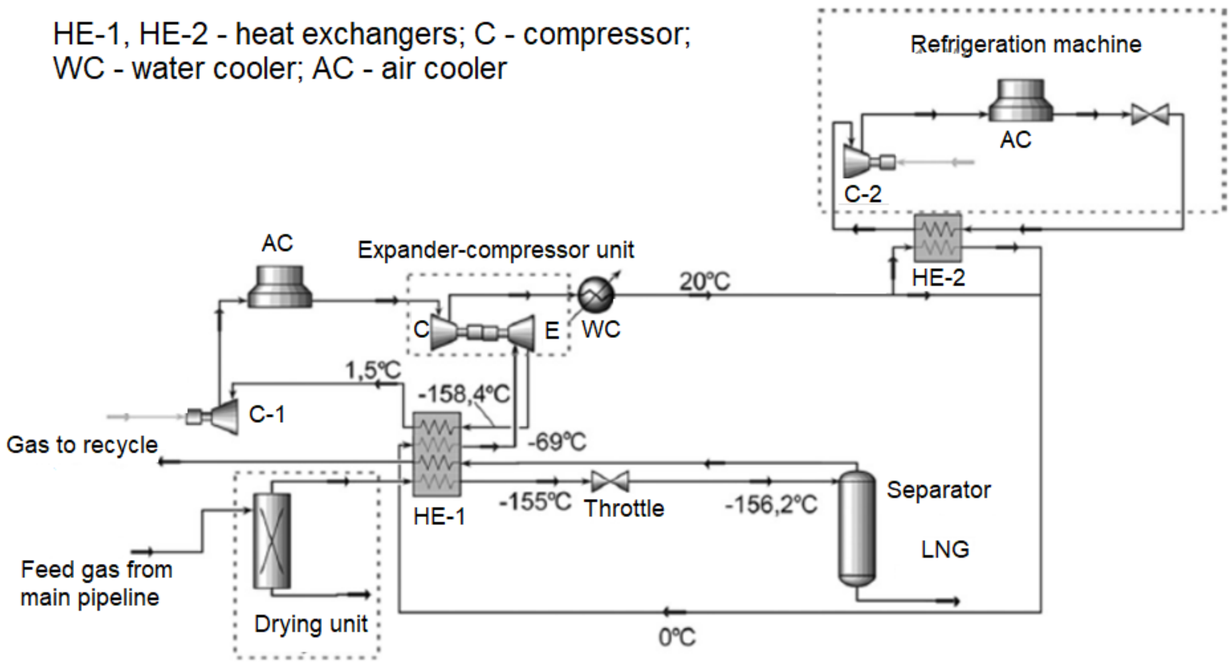

Figure 3: Nitrogen Refrigeration Cycle[19]

Efficiency increase of the nitrogen cycle by increasing the number of cooling stages leads to an increase in the number of compressors in the process. However, the use of expanders as expansion devices allows one to return part of the spent energy to the cycle. There are varieties of nitrogen refrigeration cycle with one, two and three expanders. Efficiency, number and size of expanders have a direct impact on the overall efficiency of the liquefaction process and overall productivity.

Nitrogen is not flammable, so it is the safest refrigerant. Main advantages of nitrogen cycles are the ease of starting and stopping the production line, which is important for frequent stops at plants to cover peak gas consumption loads, and the ease of adaptation to changes in the composition of feed gas[37].

3.2.1.2 The SMR Process

Technological processes using mixed refrigerants (MR) in a single-flow cycle are widely used in small-scale LNG production. The maximum capacity of the process does not exceed 1 million tons of LNG per year (62.5 tons per hour). Technological scheme of natural gas liquefaction is a classic single-flow refrigeration cycle.

Technological process of this particular scheme is based on Air Liquide's "Smartfin" gas liquefaction technology. This technology uses a single closed cycle of mixed refrigerant consisting of methane, ethane, propane, butane, and ethylene to liquefy natural gas. Mixed refrigerant is compressed, partially condensed, and expanded in several stages (figure 4).

The mixed refrigerant is compressed in the compressor C-1, cooled in the cooler 1 and partially condensed in the separator S-2. Liquid phase is sent to the heat exchanger for cooling (HE-1) and then expanded in the throttle (T-2), then mixed with the return flow of the refrigerant and counter-flow through (HE-1) is returned to the cycle.

The steam part of the refrigerant from the separator S-2 enters the compressor C-2 and at a certain pressure passes through the cooler 2, where it is cooled and then subjected to fractionation in the separator (S-3). The liquid condensed fraction is pumped out of the separator (S-3), supercooled in heat exchangers (HE-1 and HE-2) and then expanded in the throttle (T-3). Then it is mixed with the return flow of the refrigerant and sent counter-flow to the heat exchanger (HE-1).

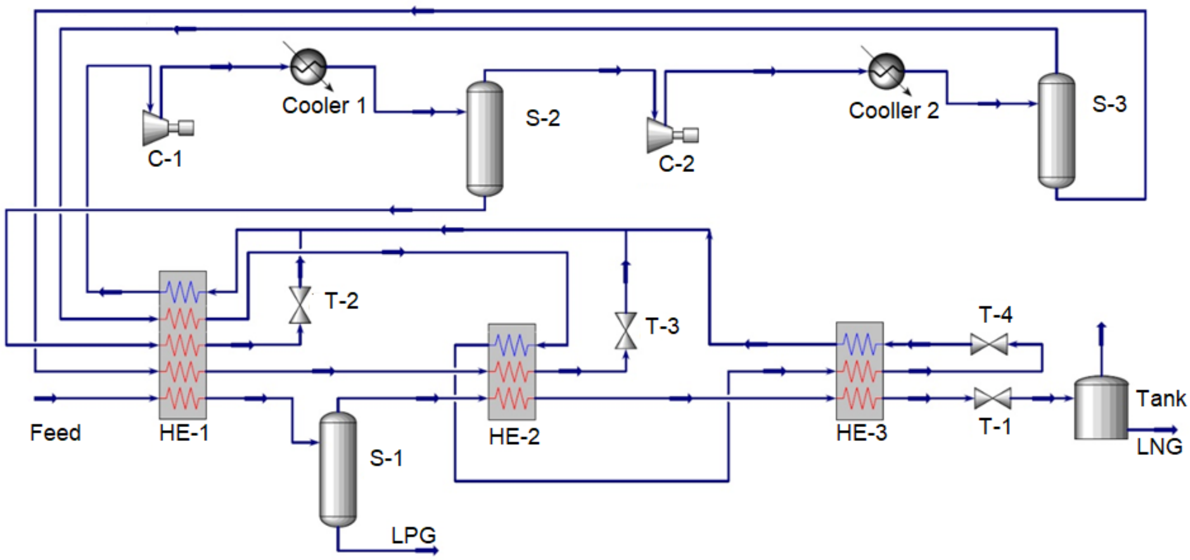

Figure 4: The SMR Process[38]

Refrigerant vapours from the separator (S-3) are cooled in heat exchangers (HE-1, HE-2), throttled (T-4) and mixed with return flow of the refrigerant, which is directed counter-flow to the heat exchanger (HE-1). Combined refrigerant mixture is sent back to the compressor suction (C-1)[39].

Cold produced by expanding parts of the refrigerant is transferred through aluminium-brazed heat exchangers to natural gas, which makes it possible to liquefy it.

Taking into account the average summer temperature of the installation area, the maximum energy consumption is 444 kWh/ton[40].

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[39] Darredeau, B. (1973). Method of Cooling a Gaseous Mixture and Installation Therefor. Patent No. US 3780535

[40] Russian Natural Gas Liquefaction Plants. (2019). The Role of LNG in Russia's Export Strategy, p. 68-81

Advantages of SMR technology:

1. Simplicity
2. Small amount of equipment
3. Reduced consumption of hydrocarbons in the refrigeration cycle

Advantages of this technology include the fact that MR components can be extracted directly from natural gas. The use of external cooling cycles for natural gas liquefaction does not require high pressure of the natural gas in main line. This makes it possible to use technologies with external cooling in natural gas fields[41].

Comparison of the nitrogen cycle and SMR cycle, suggests that with a slight difference in capital investment, when choosing a liquefaction technology, it is necessary to rely on the calculation of operating costs and on the convenience and ease of operation.

When the plant is running for a year with a constant load close to the design load, SMR cycles have obvious advantages due to lower operating costs. The disadvantages of this technology, such as increased start-up time and reduced performance when loading incomplete, are not so important in this case[42].

With frequent starts and stops of the production line, the nitrogen cycle has an undoubted advantage, since it has a short start-up period and stable efficiency at full and partial loading. Here, higher operating costs are offset by a shorter period of operation during the year.

It is also possible to use refrigeration cycles with mixed refrigerant in combination with a pre-cooling cycle. Ammonia can be used in this case. The same group includes nitrogen cooling cycles with expanders in combination with pre-cooling. However, this type is more typical for medium-and large-scale LNG production.

Usually propane is used as the pre-cooling refrigerant. The pre-cooled MR process is frequently installed in huge load LNG plants. That means there is more benefits in pre-cooling system at high capacities[43].

3.2.2 Technological Processes for Natural Gas Liquefaction Based On Expanding the Natural Gas Flow

Technological processes of liquefaction with the expansion of a part of the natural gas flow are based on the use of various expansion devices, which can act as chokes, ejectors, vortex

[41] Bronfenbrenner, J. C. (2008). On a Small-Scale. LNG Industry

[42] T. Kohler, M. Bruentrup & R.D. Key, T. Edvardsson. (2014). Choose the Best Refrigeration Technology for Small-Scale LNG Production. Hydrocarbon Processing, p. 45-52

[43] Small-Scale LNG, (2015) 2012 – 2015 Triennium Work Report. International Gas Union

tubes, expanders and cryogenerators. Since part of the natural gas flow acts as a refrigerant, the liquefaction coefficient for these processes is much lower than for processes using an external refrigerant.

Small-scale LNG production at GDS of main gas pipelines is the most efficient, since it allows using the existing pressure drop between the main and gas distribution pipelines to implement cycles with internal cooling without energy costs for gas compression in the compressor, which leads to low cost of LNG. Most energy-efficient processes are those using expansion devices with a pressure drop on the GDS, as well as high gas pressure on the CNG. Due to the fact that Russia has a network of main gas pipelines, these technologies are of the greatest interest in the country.

Taking into account the low pressure drop, cycles with expansion devices and with external cooling are widely used in the production of LNG at GDS. This ensures the necessary cooling capacity, which directly affects the liquefaction coefficient[44].

For cycles with internal cooling, the liquefaction coefficient varies between 0.03 and 0.2. In cases with external cooling, its value may increase to 0.9 or higher. However, this dramatically increases the number and cost of technological equipment, as well as the cost of its maintenance. As a result, the cost of LNG in cycles with external cooling compared to cycles with internal cooling can increase by 1.5 – 2 times. That is why cycles with internal cooling are widely used[45].

3.2.2.1 Throttling Cycle

Throttle cycles are characterized by relative simplicity and reliability, but their efficiency is low, the liquefaction coefficient is relatively low, and the working fluid pressure should be high 15.0 – 25.0 MPa.

The plant operates as part of an experimental complex for the production, storage and shipment of LNG. Natural gas, passing successively through the heat exchangers HE-1 and HE-2, is cooled, then subjected to throttling and enters the separator, where the LNG is separated (figure 5).

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[44] Gorbachev S. P., Koposov A. I. (2008). Evaluating the Efficiency of Small-Scale LNG Production at Gas Distribution Stations. Russian Gas Industry. Current Aspects, p. 50-53

[45] Gorbachev S. P., Medvedkov I. S. (2012). Effect of High-Boiling Components in LNG Production at GDS. Transport on Alternative Fuel, p. 48-54

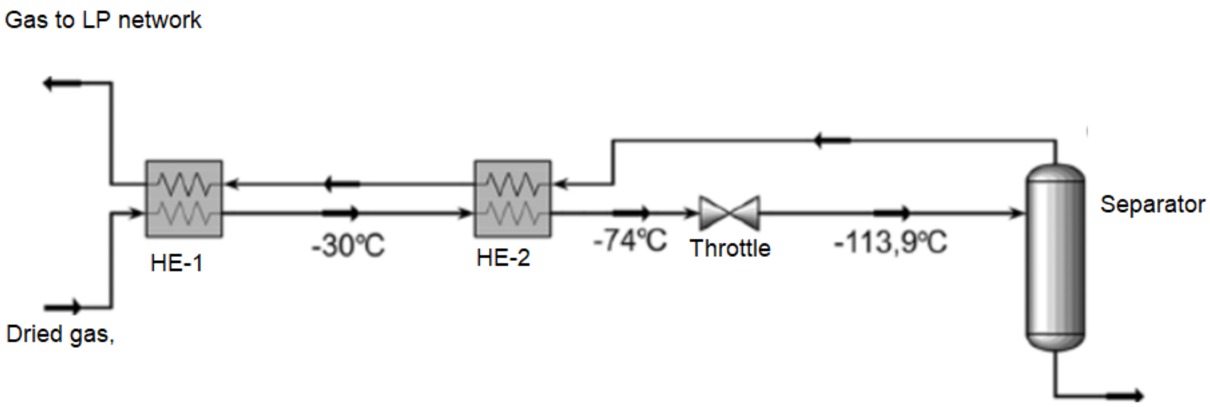

Figure 5: Throttling Cycle[19]

The main advantage of this plant, as well as all other plants that operate in cycles with internal cooling, is very low energy consumption (10 kWh/ton) for LNG production. Proposed liquefaction technology for GDS also has fundamental drawbacks as follows:

1. A limited base for application, since a significant part of the Russian GDS is characterized by either low (3.3 – 3.5 MPa) and unstable input pressure values, or significant seasonal flow drops (4 – 5 times), which leads to almost complete loss of productivity of this type of installation, downtime and inefficient use of operating personnel
2. Low productivity due to low liquefaction coefficient (about 0.02)
3. Low product quality due to the significant content of high-boiling hydrocarbon fractions and carbon dioxide in the initial and, consequently, the finished product

The share of high-boiling components in LNG also increases due to the significant vapour content behind the plant's throttle (98% and higher). All this entails a restriction on the use of products as motor fuel, since such products do not comply with GOST 56021-2014 "Liquefied natural gas. Fuel for internal-combustion engine and generating unit. Specifications"[19].

3.2.2.2 Throttling Cycle with a Vortex Tube

The disadvantages of a simple throttle cycle created prerequisites for the transition to a qualitatively new stage of creating typical liquefaction plants that are specially optimized for operation in a wide range of technical characteristics and technological parameters.

The unit operates at the expense of the pressure drop available at the GDS, using a vortex tube for additional cooling of the liquefied gas without using external energy sources. The principle of operation of the vortex tube is based on the vortex effect. The essence of the vortex effect is to reduce the temperature in the central layers of the swirling gas flow (free vortex) and increase the temperature of the peripheral layers. With the appropriate design of the device, the gas vortex can be divided into two streams: with low and high temperatures.

The gas from the main pipeline enters the heat exchanger, where it is cleaned from carbon dioxide and dried. Heat exchanger HE-1 and HE-2 work alternately (figure 6). After that, gas enters the vortex tube, where it expands and cools. The vapour-liquid mixture is divided into LNG and gas, which is sent back to the distribution pipeline. The stream expanded in the vortex tube is connected to the return flow at the entrance to the heat exchanger HE-1. The liquefaction coefficient for the vortex tube scheme increases slightly compared to cycles with simple throttling and is estimated to be about 0.04. Electricity is used only for control and automation equipment and household needs (10 kWh/ton).

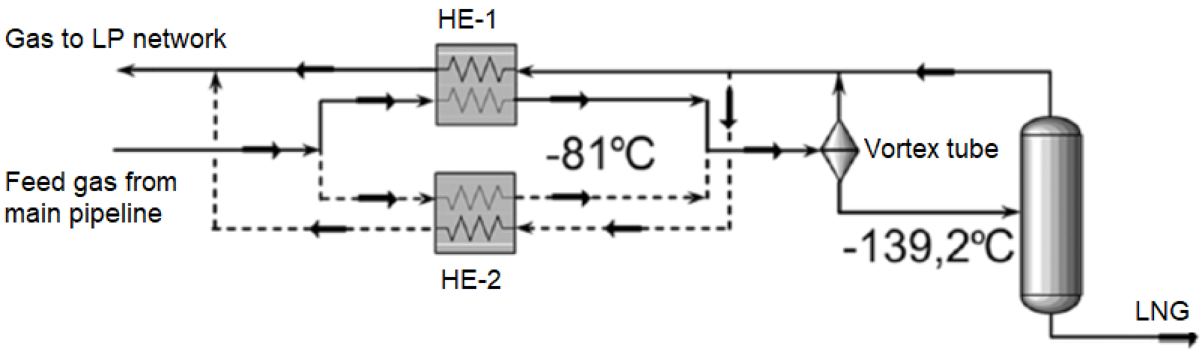

Figure 6: Throttling Cycle with a Vortex Tube[19]

The main drawback of schemes using a vortex tube is the need to experimentally determine the parameters of its operation in each case. It should also be noted that a correct operation of the vortex tube requires a clear adjustment of control and measurement equipment and stability of the feed flow pressure. In addition, the use of alternately working heat exchangers leads to instability of the entire installation, as well as to unpredictable quality of the product. In addition, it is advisable to use such installations only at stations with a large flow rate and high pressure of the incoming gas.

3.2.2.3 Throttle-expander Cycle

In small-scale LNG production, expander cycles of various modifications are used. There is an option when the expander is used in a cycle where the working medium is the natural gas itself.

This type of process is fruitful when a facility is installed where a huge volume of gas is let down from a high-pressure to a low-pressure gas distribution system on a daily basis. This cycle is usually applied with minimal compression, which helps reduce power requirements. As a rule, about 15%–18% of the feed gas is liquefied in the process after processing a large volume of incoming gas. The rest goes to a low-pressure pipeline[46].

[46] Price B., Mahaley M., Shimer W. Optimize Small-Scale LNG Production with Modular SMR Technology. (Gulf Publishing Holdings LLC)
Retrieved from: http://www.gasprocessingnews.com/features/201404/optimize-small-scale-lng-production-with-modular-smr-technology.aspx

In fact, the facility is an energy efficient GDS that produces two products for gas consumption: LNG and natural gas.

The liquefaction coefficient when using this technology does not exceed 0.2, but it has the lowest specific energy consumption. The main energy is spent on gas cleaning and drying (10 kWh/ton).

The facility works in the following order. High-pressure natural gas coming from GDS to the facility entrance is divided into two streams (figure 7). First stream is passed to the cleaning and drying unit, second one is used for heat recovery. The drained and purified gas is compressed using a compressor that is driven by the torque obtained in the expander. Connected by a single shaft and placed in the same housing, the compressor and expander form an expander-compressor unit.

Then the compressed gas is cooled in the heat exchanger HE-1, heating the gas of the heat recovery line.

After heat exchanger HE-1, gas is divided into two lines: the process flow (for cold generation) and the production flow (for liquefying natural gas). The process flow through the heat exchanger HE-2 is directed to the expander, which rotates the expander turbine. Next, the cold flow from the expander outlet is added to the return flow of vapour from the separator. Resulting mixture is fed counter-flow to the main heat exchanger HE-2, through the heat exchanger HE-3 to cool the production flow. The main cooling is provided by this flow.

The gas from the upper part of the separator S-1 after passing the input throttle and pressure relief is at a lower temperature than before the throttle. This gas stream is used for cooling in the heat exchanger HE-3. After passing the heat exchangers HE-2 and HE-3 in the opposite direction, it is combined with the flow for heat recovery from the units of the facility and with the flow of gas released from the LNG tank, and then sent to the gas distribution network.

Purified production flow is passed through heat exchangers, where compressed gas is cooled by the return flow of the uncompressed part of the production flow gas from the separator mixed with the cold flow from the expander. Then the production flow is passed through a choke, after which the product enters the container in the form of a vapour-liquid mixture. Here, the liquid (LNG) is separated from the cold vapour, which is discharged through heat exchangers into the distribution pipeline[47].

[47] Gaydt D.D., Mishin O.L. (2015). A Method for Producing Liquefied Natural Gas. Patent No. 2541360

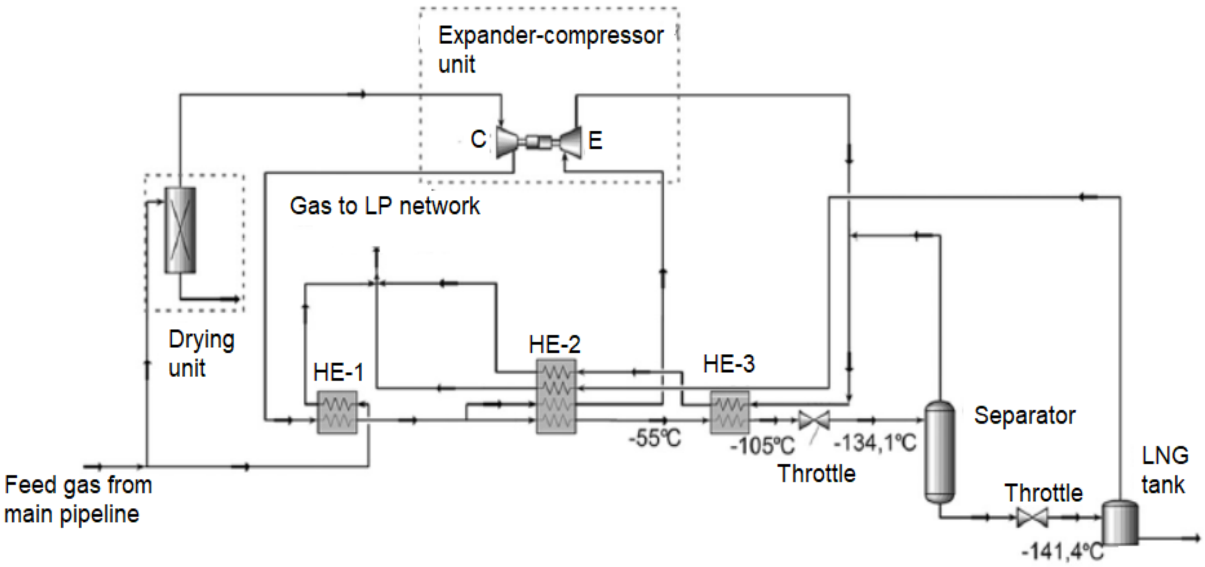

Figure 7: Throttle-Expander Cycle[19]

The facility does not consume external energy for the liquefaction of natural gas apart from some auxiliary systems, a cryogenic pump, and the drive of the expander's lubrication pump. However, the liquefaction rate is low at 0.11.

The main drawback of this scheme is the expander location in the direct gas flow, which entails a restriction on the degree of liquefaction.

The features of this plant in contrast to traditional liquefaction plants are as follows[48]:

1. In the main gas pipeline, therefore, at the entrance to the installation, there are both daily and seasonal pressure fluctuations in a wide range of values, which leads to changes in the performance of the installation
2. Because of the inconsistency of LNG production and consumption, there is a need to regulate (in particular, reduce) the cooling capacity of the plant
3. At a low temperature of the gas behind the expander, the vapors of carbon dioxide and compressor oil contained in the source gas can crystallize

3.2.3 Combined Cycles

3.2.3.1 A High-Pressure Throttling Cycle with Freon Pre-Cooling at CNG Stations

In the production of high-quality LNG, it is better not to use refrigeration cycles that use only throttling, because of the low degree of liquefaction and, as a consequence, the high

[48] Gorbachev S. P., Loginov A. A. (2008). Features of LNG Manufacture on Gas Distribution Stations at Variable Pressure in the Main Gas Pipelines. Transport on Alternative Fuel, p. 66-69

concentration of heavy impurities in the liquid phase, so only processes with an external refrigeration machine are applicable for the production of high-quality LNG.

A high-pressure throttling cycle with freon pre-cooling at the CNG is a technological equipment for LNG production, mounted in containers and blocks.

Natural gas after the CNG station compressor units is purified from mechanical impurities and measured (figure 8). Then gas enters the heat exchanger unit, where it is sequentially cooled in three heat exchangers (HE-1, HE-2, HE-3) to a temperature of – 80 °C: in the first and third ones cooling is carried out by the reverse flow of LNG vapours, and in the second one – by liquid freon from the refrigeration machine. After that, natural gas is fed to throttling and consequently is cooled to a liquid phase formation temperature of – 120 °C. Then gas enters the separator unit to ensure quality separation of the liquid phase (LNG) from the gaseous one. From the separator it is sent through the throttle unit, where the LNG pressure is reduced even more, to the LNG storage tank at a temperature of – 141.7 °C. The gaseous component from the separator is sent through heat exchangers, where it is heated to a temperature of +5...+10 °C, to the suction line of the CNG station compression unit[49].

The refrigeration machine has two freon circuits. The first freon circuit serves to cool the second-circuit freon, and freon from the second circuit is fed to the heat exchanger to cool the direct flow of natural gas.

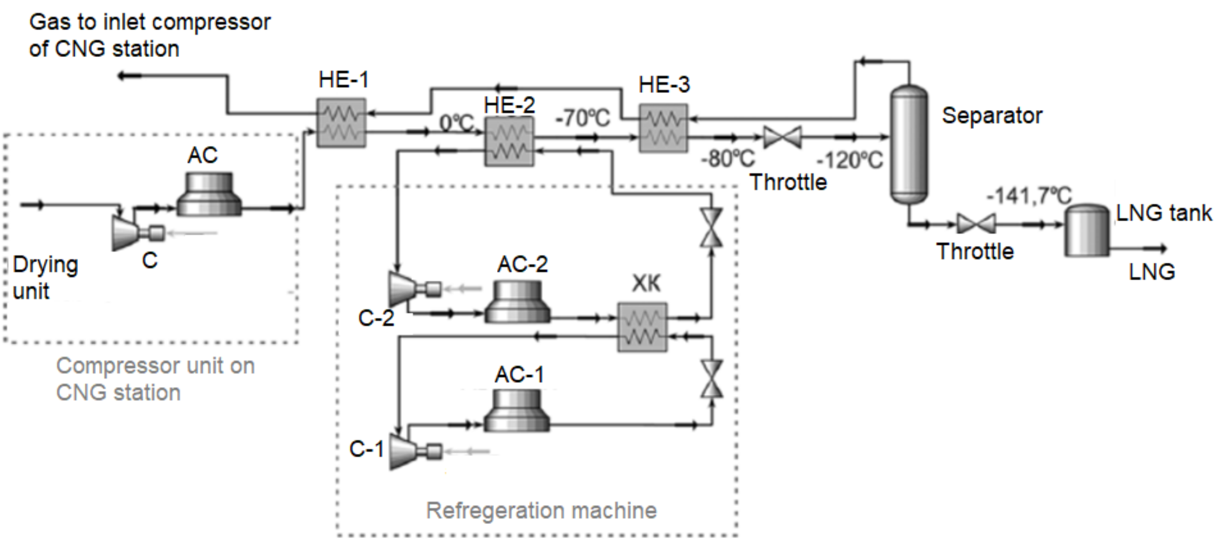

Figure 8: A High-Pressure Throttling Cycle with Freon Pre-Cooling[19]

The disadvantages of this scheme include the complete dependence of resulting LNG composition on composition of gas supplied to the CNG station, and the inability to correct it. In addition, when the consumption of compressed natural gas at the CNG station is low, it is

[49] Popov N. A., Belov M. B. (2011). Creating Natural Gas Liquefaction Plant and the Introduction of Effective LNG Technologies. Gas Filling Station + Alternative Fuel, p. 17-20

difficult to use the non-liquefied gas flow. In addition, there is high energy consumption (870 kWh/ton).

3.2.3.2 A High-Pressure Throttle-Ejector Cycle with Freon Pre-Cooling

The special aspect of this technology is the high initial gas pressure. This technology is well known and used on installations in Russia. It has a higher liquefaction coefficient than the technologies used on GDS (up to 0.5) and a relatively low specific energy consumption.

Compressed to a high pressure, feed gas is sent to the drying unit, where it is dried to the water dew point not higher than – 90 °C, and then sent to the liquefaction unit. There, high-pressure gas is sequentially cooled in the heat exchangers HE-1, HE-3 and the evaporator of the refrigeration machine HE-2 and sent to expand into the ejector as a working stream, in which the gas pressure is reduced.

The gist of the gas ejector (E) operation is that the low-pressure gas rushes into the mixing chamber due to the fact that a vacuum region is created there (the pressure is lower than the low-pressure gas pressure). The vacuum region is created when a high-pressure gas passes at high speed and pressure through a supersonic nozzle (narrowing section). In the mixing chamber, two streams are combined and a mixed stream is formed. After passing the mixing chamber, the flow rushes into the diffuser, where it is slowed down and the pressure increases. At the outlet of the ejector, the mixed flow has a pressure higher than the pressure of the low-pressure gas. It is important to note that increasing the pressure of low-pressure gas occurs without spending external energy. Expanded gas in the ejector is fed to the separator. Liquid fraction separated in the separator is throttled to a low pressure and sent to the LNG storage tank, from which the LNG is distributed to the consumer, and the steam is pressed into the ejector due to the energy of the working flow expansion. Steam fraction from the separator passes through the heat exchangers HE-1 and HE-2 as a return flow for cold recovery, after which a circulation compressor compresses the return flow to a high pressure, mixed with a new portion of the drained feed gas and sent back to the liquefaction unit.

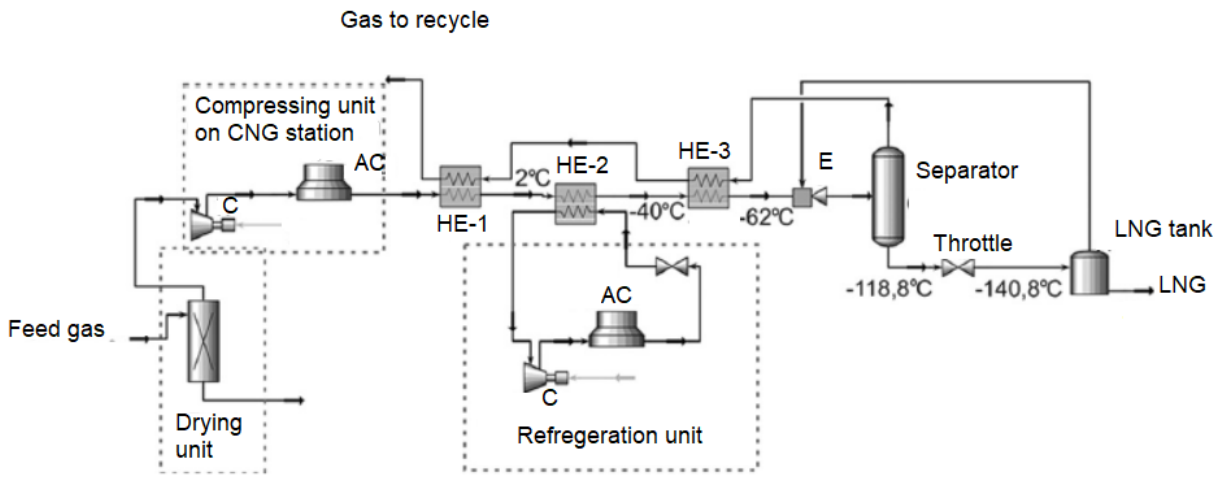

Figure 9: A High-Pressure Throttle-Ejector Cycle with Freon Pre-Cooling[19]

It should also be noted that the use of an ejector makes it possible to maintain the pressure in the circuit at a certain level. Main advantages of the proposed scheme are its simplicity, reliability and solid experience in operating installations that implement this scheme. The coefficient for natural gas liquefaction is 0.48. Estimated specific energy costs are 360 kWh/ton.

The disadvantages of this type of scheme are the narrow ranges of the optimal scheme and the disadvantages that are typical for liquefaction schemes on CNG stations, which have already been discussed above.

3.3 Selection of the Liquefaction Process for Further Research

The choice of liquefaction technology is based on the selection of the base facility for LNG production. In the European part of Russia with a developed gas transportation system, it is most appropriate to place small-scale LNG production at GDS and CNG stations with a 0.1 – 0.2 liquefaction rate. In the Asian part of the Russian Federation, especially in the North, small and medium-sized natural gas fields can become a resource base for LNG production. For such fields, LNG production technologies with 100% liquefaction are required, that is, using a nitrogen cycle or a mixed refrigerant cycle extracted locally from natural gas, as well as using the most affordable and efficient gas preparation techniques and technologies. In addition, when using a technology with a low liquefaction coefficient, higher-boiling hydrocarbons are first condensed from the gas, which results in their high content in the liquefied gas. This reduces the energy efficiency of LNG use and limits the scope of its application. When choosing a small-scale process, the following basic principles are taken into account: thermodynamic efficiency, safety, and minimum operating costs[18].

Table 2: Comparison of the Considered Liquefaction Processes

Type	Advantages	Disadvantages
Nitrogen Cycle	The liquefaction coefficient is almost 0.99 Good quality of LNG Fast start-up Stable process when fully or partially loaded Safe refrigerant (N_2) and ability to adapt to changes in the composition of feed gas	Liquefaction temperature of N_2 is higher than the one of CH_4 High energy consumption
The SMR Process	Simplicity Mixed refrigerant might be obtained from feed gas High pressure of feed gas OPEX is lower than for nitrogen cycle Ability to adapt to changes in the composition of feed gas	Long start-up time Must be fully loaded to maintain effective production Poor exploitation experience of considered process

Throttling Cycle	Simple and safe Minimal energy consumption No need in compression due to transition from HP to LP	Poor production and liquefaction coefficient 0.02 Poor quality of LNG Seasonal reduction in supply of feed gas at GDS Too much vaporization downstream of throttle
Throttling Cycle with a Vortex Tube	Minimal energy consumption Pressure gradient of GDS is used Additional cooling without external sources of energy	Liquefaction coefficient 0.02 The need to experimentally determine the parameters of operation in each case Feed pressure must be stable
Throttle-Expander Cycle	No need in compression due to transition from HP to LP Minimal energy consumption No need in external energy to liquefy natural gas	Restriction in liquefaction rate because expander is in the direct gas flow Downstream of expander there might be crystallization of impurities
Throttling Cycle with pre-cooling	Liquefaction coefficient 0.47 Good quality of LNG	High energy consumption considering compression on CNG station LNG quality depends on the feed gas composition High flow rate is needed
Throttle-Ejector Cycle	Liquefaction coefficient 0.48 Low energy consumption Easy to maintain pressure in the circuit	LNG quality depends on the feed gas composition High flow rate is needed

According to a recent report by Gazprom, only 22 regions of the Russian Federation will participate in the program for advanced development of the GMF infrastructure, which is planned to allocate more than 2.7 billion rubbles from the federal and regional budgets in 2020-2022. The most significant total amount of funding for three years from the federal budget will be received by the regions of the Volga Federal District (more than 300 million rubbles)[2].

Today this district is one of the leaders in the development of the GMF market. In the district, gas motor fuel consumption is growing at a faster rate than in other areas, and the level of loading of the gas filling infrastructure is increasing. In particular, all types of automotive equipment (trucks, buses, cars) equipped with engines running on GMF are manufactured there. Now, the number of gas filling infrastructure facilities in the district has increased 4 times compared to 2015 and Volga Federal District is one of the leaders in the development of the LNG infrastructure. This is justified by the developed logistics flows of cargo transportation and agriculture. In addition, 8 out of 14 federal subjects from this district were included in the list of "pilot" regions for the implementation of projects for the transfer of transport to the GMF[50].

Currently, Republic of Tatarstan and Republic of Bashkortostan are the leaders in the use of natural gas as a motor fuel. Thus, Republic of Tatarstan has formed its own three-year program that provides for the construction of 10 CNG filling stations annually[51].

Gas motor fuel is also in high demand in Siberian Federal district. In some regions, most public transport has already switched to using GMF. Furthermore, switching to the GMF may be more profitable particularly for public transport, since it is used very intensively.

In the future, LPG may become even more widespread within industry in this district, since gas fields are located there, so if processing facilities are available, there will be an opportunity to produce fuel at lower prices, due to the close location of sales market.

Gas reserves that have access to the Power of Siberia account for 60% of the total gas reserves of Yakutia and the Irkutsk region, and remaining 40% of reserves are restricted and isolated. Small-scale LNG production is currently the only option for gas monetization in Eastern Siberia.

Today, pilot dump trucks of some Kuzbass coal mining companies are being prepared for conversion to gas motor fuel. The government of Kuzbass has prepared projects for the development of a regional program for integrated development of the liquefied natural gas market based on the main consumers – Kuzbass mining enterprises. This project also includes the refuelling infrastructure development for public sector[52].

Taking into account the sufficiently developed infrastructure and potential of the region, a high-pressure throttling cycle with freon pre-cooling, located at the CNG filling station is considered a more acceptable gas liquefaction technology.

Based on the performed analysis and in accordance with the objective set in the chapter one, the following tasks were identified:

1. It is planned to use a certain amount of produced liquefied natural gas that will precool the incoming gas. As a result, it will make possible a freon refrigerating unit replacement

[50]V. Arhireev, (2017). Gas Motor Fuel Market in Russia: Is There Any Prospect of Moving Away from Oil? REGNUM, News Agency. Retrieved from: https://regnum.ru/news/economy/2275425.html

[51] In 2019, 4 Billion Rubles of Subsidies Can Be Allocated for the Development of the Gas Motor Fuel Market, EnergyLand.info, Analytics – Oil and Gas, Retrieved from: http://www.energyland.info/analitic-show-181562

[52]Liquefied Natural Gas in Quarry Equipment Project is Presented at the International Forum by REC "Kuzbass", (2019), Administration of Kuzbass Government,
Retrieved from: https://ako.ru/news/detail/proekt-nots-kuzbass-po-ispolzovaniyu-szhizhennogo-prirodnogo-gaza-na-karernoy-tekhnike-predstavlen-n

and ensure the self-sufficiency of the scheme and maximum use of free cold in the system, while minimizing the energy costs for liquefying natural gas

2. Carry out effectiveness evaluation of obtained results

4 Methodology

The tasks identified in the previous Chapter will be performed in the Aspen HYSYS simulation environment.

4.1 Input Data

Since the liquefaction unit is located at CNG station, it is assumed that feed gas will get in there from the main pipeline. It means that feed gas supplied for liquefaction will meet certain requirements in terms of its component composition. Technical requirements for the composition of natural gas transported through the main pipeline are currently regulated by the following standard: STO Gazprom 089-2010 "Natural gas, supplied and transported via main gas pipelines. Technical condition"[53].

In this thesis, gas composition shown in table 3 will be used.

Table 3: Feed Gas Composition

Component	Mole Fraction
Methane	0.90
Ethane	0.050
Propane	0.026
n-Butane	0.0115
i-Butane	0.0092
n-Pentane	0.0029
i-Pentane	0.0004

In accordance with the scheme selected in Chapter 3, the refrigerant used is carbon tetrafluoride (R-14) with the chemical formula CF_4 and a boiling point of minus 128 ℃. Mass flow of refrigerant and its initial pressure are equal to 5889 kg/h and 1 MPa respectively in both circuits.

Initial parameters of feed gas are as follows:

1. Temperature 20 ℃
2. Pressure 5.5 MPa
3. Molar flow 2300 m^3/h

[53] STO Gazprom 089-2010 "Natural gas, supplied and transported via main gas pipelines. Technical conditions".

In accordance with the scheme selected in Chapter 3, temperatures after main heat exchangers HE-1, HE-2, and HE-3 equal 0 ℃, minus 70 ℃, and minus 80 ℃ respectively.

Natural gas pressure before entering the first heat exchanger is 20 MPa.

Throttle pressure equals 1 MPa and storage pressure equals 0.4 MPa.

4.2 Simulation Model

Simulation is impossible without a property package selection that is based on certain equations of state.

An equation of state is a relation that reflects for a particular class of thermodynamic systems the relationship between main physical quantities that characterize it, such as temperature, pressure, volume, chemical potential, entropy, internal energy, and enthalpy. Equations of state are necessary for obtaining specific results concerning the system using the thermodynamics. These equations are not contained in the postulates of thermodynamics, so for each object selected for study, they are either determined empirically, or for the model of the system being studied, they are found by methods of statistical physics. In the framework of thermodynamics, the equations of state are considered to be given when defining a system. If the object under study allows a thermodynamic description, then this description is performed by means of equations of state, which for real substances can have a very complex form[54].

In Aspen HYSYS, several equations of state meet the goals of this simulation, the main ones are as follows:

1. Peng-Robinson (PR)
2. Peng–Robinson–Stryjek–Vera (PRSV)
3. Soave-Redlich-Kwong (SRK)

However, Peng-Robinson equation of state is sufficient for most oil and gas processes. This equation describes a variety of systems pretty well (from low-temperature cryogenic systems to high-temperature and high-pressure systems) in a wide range of conditions: temperature is higher than minus 271°C and pressure is less than 100,000 kPa.

The advantage of the equation is that the properties of a pure gas are described by this equation using only three individual properties: the temperature and pressure of the critical point of the gas, as well as the acentric factor. These parameters are defined for a wide range of substances.

[54] Rudoy Y. G. (2017). Equation of State. Great Russian Encyclopedia. p. 65

When calculating mixtures, the mixture is considered as a hypothetical gas which critical point parameters are a known function of the concentrations of the initial components and the thermodynamic parameters of their critical points[55].

Although the Soave-Redlich-Kwong equation of state presents similar results, its scope is more limited than that of Peng-Robinson equation (temperature is higher than minus 143°C and pressure is less than 35,000 kPa), and it is not as reliable for calculating non-ideal systems.

As for Peng-Robinson-Stryjek-Vera equation of state, its application is similar to that of Peng-Robinson and presents results of similar or even better accuracy. However, this equation requires a longer calculation time and additional interaction parameters required for the equation.

In this case, the most suitable equation of state is Peng-Robinson. Its property package perfectly fits cryogenic gas processing calculations.

4.3 Assumptions

The following assumptions were made before the simulation has begun:

1. Feed gas is supplied to the liquefaction unit after additional cleaning, accounting and other operations of CNG station
2. Pressure drop in heat exchanger is neglected
3. In order to not consider a drying unit in this system, it is assumed that drying unit is in place before entering liquefaction unit and there is no water in the gas stream
4. Since no traces of water in the gas stream are presented, hydrate formation does not occur so there is no need for inhibition
5. There is no heat exchange with the environment
6. Calculations of LNG heat exchangers are performed with a default tolerance of 10^{-4} with a maximum number of iterations equal to 25

Tolerance is defined as the relative discrepancy of the energy balance equation. It means that a certain calculation error is established (in this case, 10^{-4}), and when it is reached in the range of a given number of iterations, the calculation is considered to be converged[56].

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[55] Reid, R., Prausnitz, J., and Sherwood, T. (1982) Properties of Gases and Liquids: a Reference Guide. Chemistry. p. 592.

[56] Aspen HYSYS V8.8 Help

5 Simulation and Results

5.1 Analysis of Original Scheme

5.1.1 Process Flow Diagram Description

The scheme that was selected in Chapter 3 looks as shown in figure 10.

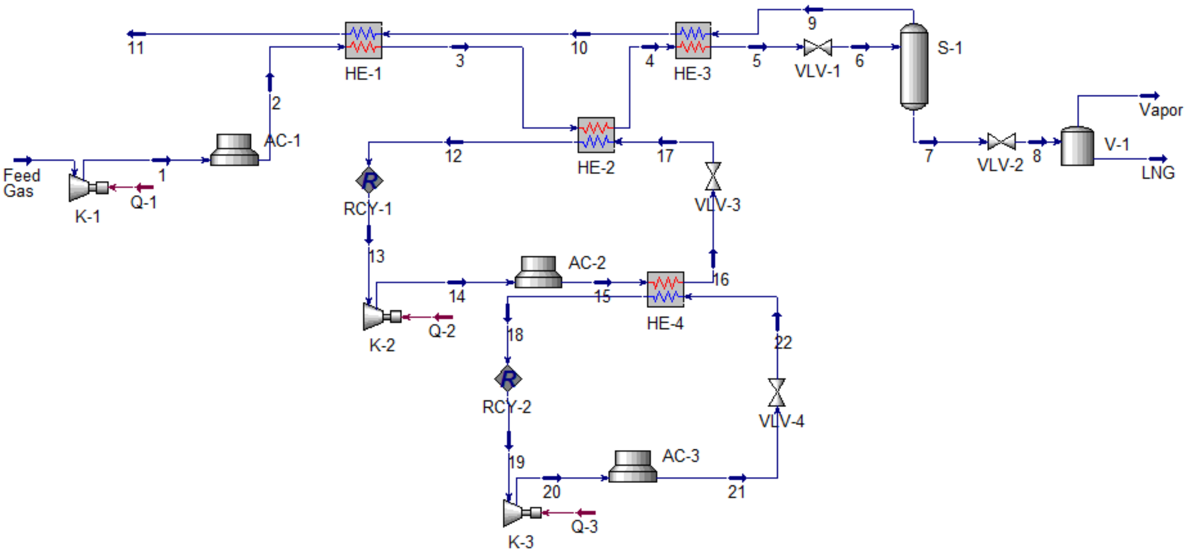

Figure 10: Process Flow Diagram of Original Scheme

Feed gas is delivered to the CNG compressor units (K-1) with a pressure of 5.5 MPa and a temperature of plus 20 ℃, where it is compressed to operating pressure of the liquefaction unit equal to 20 MPa. It entails a temperature of gas swell to plus 146.5 ℃ (stream 1). In the air-cooling unit (AC-1), its temperature drops to plus 40 ℃ (stream 2). Then feed gas enters a block of three heat exchangers (HE-1, HE-2, and HE-3). In heat exchanger HE-1, it is cooled to 0 ℃ (stream 3). After that it is completely condensed at a temperature of minus 70 ℃ in heat exchanger HE-2 (stream 4) and further cooled to a temperature of minus 80 ℃ in heat exchanger HE-3 (stream 5).

The next stage is throttling. After heat exchangers, liquid flow passes through the block of throttles (VLV-1), where its pressure is reduced to 1 MPa and consequently its temperature to minus 120 ℃ (stream 6). It makes a part of the liquid flow to evaporate. Then gas-liquid flow enters the separator (S-1) to separate liquid and gas phases. Liquid phase (stream 7) with a pressure of 1 MPa and a temperature of minus 120 ℃ is throttled (VLV-2) to a pressure of 0.4 MPa. It entails gas cooling to a temperature of minus 141.2 ℃, resulting in partial evaporation (stream 8). Vaporized part of the stream (stream Vapor) is separated in LNG tank (V-1), and final product with a pressure of 0.4 MPa and a temperature of minus 141.2 ℃ (stream LNG) goes to consumers. Its composition (see table 4) corresponds to LNG of grade C in accordance with GOST R 56021-2014 "Liquefied natural gas. Fuel for internal-combustion engine and generating unit. Specifications"[32].

Table 4: LNG Composition from Original Scheme

Component	Mole Fraction
Methane	0.7998
Ethane	0.094
Propane	0.0508
n-Butane	0.0224
i-Butane	0.0195
n-Pentane	0.0067
i-Pentane	0.0067

The gaseous component with a pressure of 1 MPa and a temperature of minus 120 ℃ (stream 9) from the separator passes through heat exchangers HE-3 and HE-1 to the suction line of the CNG station compression unit. In heat exchangers HE-3 and HE-1, the reverse flow of LNG vapor absorbs heat from the gas going along the main line, thereby sequentially being heated to temperatures of minus 77.4 ℃ and plus 28.5 ℃, respectively (stream 10 and stream 11).

As for the refrigeration machine, it has two freon circuits.

The first circuit is used for cooling the direct flow of natural gas in heat exchanger HE-2. Refrigerant at a pressure of 1 MPa (stream 13) is compressed to a pressure of 15 MPa (stream 14) in compressor K-2, what leads to temperature increase up to plus 163.8 ℃. In the air-cooling unit (AC-2), its temperature is reduced to plus 40 ℃ (stream 15), and then in heat exchanger HE-4 – to minus 10 ℃ (stream 16). Further, gaseous refrigerant is throttled (VLV-3) to a pressure of 1 MPa. At the same time, it is cooled to minus 84.5 ℃ (stream 17) and partially condensed. After this, the gas-liquid flow is fed to heat exchanger HE-2, where liquid part of refrigerant is vaporized, and heat is absorbed from feed gas stream from the main line. After that, gaseous refrigerant has a temperature of plus 0.97 ℃ (stream 12).

The second circuit is used for cooling the first circuit refrigerant. Refrigerant at a pressure of 1 MPa (stream 19) is compressed to a pressure of 15 MPa (stream 20) in compressor K-3, what leads to a temperature increase up to plus 209.3 ℃. In the air-cooling unit, its temperature is reduced to plus 30 ℃ (stream 21). Then, gaseous refrigerant is throttled (VLV-4) to a pressure of 1 MPa. At the same time, it is cooled to minus 44.7 ℃ (stream 22) without state changing. Further, gaseous refrigerant is fed to heat exchanger HE-4, where it absorbs heat from the main circuit refrigerant and heats up to a temperature of plus 39.7 ℃ without phase changing (stream 18).

All streams mentioned above are presented in tables 5, 6, and 7 along with their major physical properties.

Table 5: Streams of the Main Line with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
Feed gas	1	5.5	20	1550
1	1	20	146.5	1550
2	1	20	40	1550
3	1	20	0	1550
4	0	20	-70	1550
5	0	20	-80	1550
6	0.38	1.2	-120	1550
7	0	1.2	-120	974.2
8	0.18	0.4	-141.2	974.2
LNG	0	0.4	-141.2	805.4
Vapor	1	0.4	-141.2	168.8
9	1	1	-120	575.8
10	1	1	-77.4	575.8
11	1	1	28.5	575.8

Table 6: Streams of the First Refrigeration Circuit with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
12	1	1	0.97	5889
13	1	1	0.97	5889
14	1	15	163.8	5889
15	1	15	40	5889
16	1	15	-10	5889
17	0.8	1	-84.5	5889

Table 7: Streams of the Second Refrigeration Circuit with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
18	1	1	39.7	5889
19	1	1	39.7	5889
20	1	15	209.3	5889
21	1	15	30	5889
22	1	1	-44.7	5889

5.1.2 Heat Exchangers

There are many types of heat exchanger but one of the most effective heat transfers occur in coil-wound heat exchangers (CWHE). Heat transfer coefficients in these heat exchangers are on average 1.5 – 2 times higher than in shell-and-tube heat exchangers. CWHE operate in a wide range of temperatures and pressures and are compact and reliable. They are widely used for both large- and small-scale LNG production.

In general, a coil-wound heat exchanger consists of several layers of tubes wound on a central pipe (core rod). Small gaps are left between pipe layers and between individual pipes using gaskets. CWHE are made of stainless steel, aluminium alloys, carbon steel and special alloys.

Design of coil-wound heat exchanger offered by the Linde Group is depicted in figure 11.

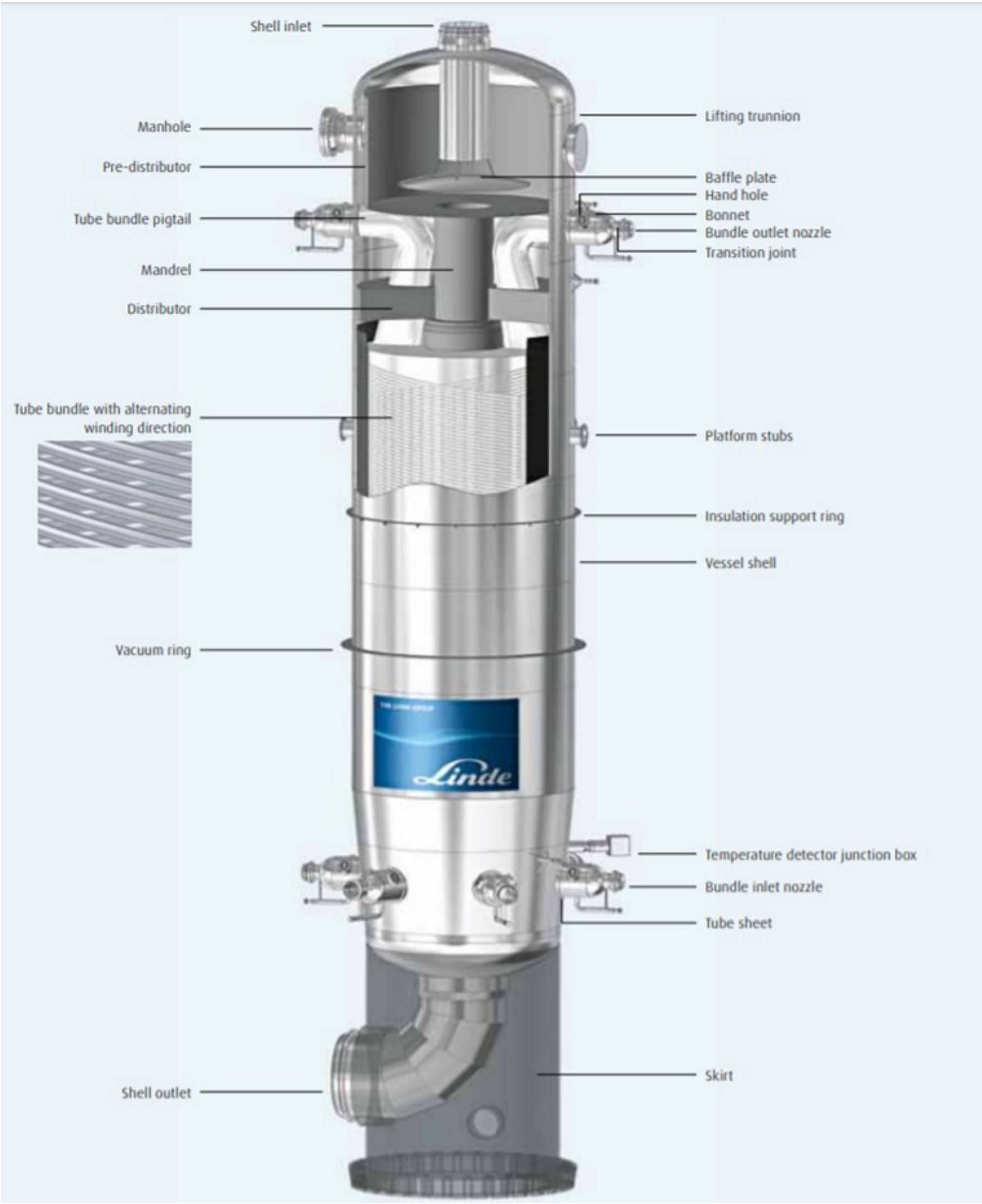

Figure 11: Design of Coil-wound Heat Exchanger[57]

[57] Coil-wound Heat Exchangers (2018), Linde Ag, Retrieved from: https://www.linde-engineering.com/en/index.html

5.1.3 Calculation of Liquefaction Coefficient

Liquefaction coefficient is calculated as shown in Eq. 1[45]

$$K_l = \frac{L}{G} \tag{Eq. 1}$$

Where K_l is liquefaction coefficient, L is mass flow of liquefied gas (kg/h) and G is mass flow of feed gas (kg/h).

According to table 4 and Eq. 1

$$K_l = \frac{805.4}{1550} = 0.52$$

5.1.4 Calculation of Approximate Molar Flow of Fuel Gas

Compressors' power consumption obtained during simulation is presented in table 8.

Table 8: Compressors' Power Consumption

№ of compressor	**Power, [kW]**
K-1	115.6
K-2	173.3
K-3	201.6

Approximate molar flow of fuel gas for three compressors is calculated as shown in Eq. 2

$$Q_{fuel\ gas} = \frac{3600 \cdot P}{\lambda \cdot \eta} \tag{Eq. 2}$$

Where $Q_{fuel\ gas}$ is an approximate molar flow of fuel gas (m^3/h), P is the total power of three compressors (J/s), λ is the net heating value of fuel gas (MJ/m^3) and η is the adiabatic efficiency.

Adiabatic efficiency takes into account hydraulic losses and the resulting increase in polytrophic work compared to adiabatic.

The default value of adiabatic efficiency set by Aspen HYSYS

$$\eta = 0.75$$

According to GOST 5542-2014 "Natural fuel gases for commercial and domestic use. Specifications"[58]

$$\lambda = 35\ MJ/m^3$$

Based on data presented in table 8

$$Q_{fuel\ gas} = \frac{3600 \cdot (115.6 + 173.3 + 201.6) \cdot 1000}{35000000 \cdot 0.75} = 67.3\ m^3/h$$

5.1.5 Main Parameters of Original Scheme Heat Exchangers

Plots of mean temperature difference based on the HYSYS calculation data clearly show a heat transfer process (figures 12-15). In this case, the logarithmic mean temperature difference characterizes heat transfer driving force in used heat exchangers.

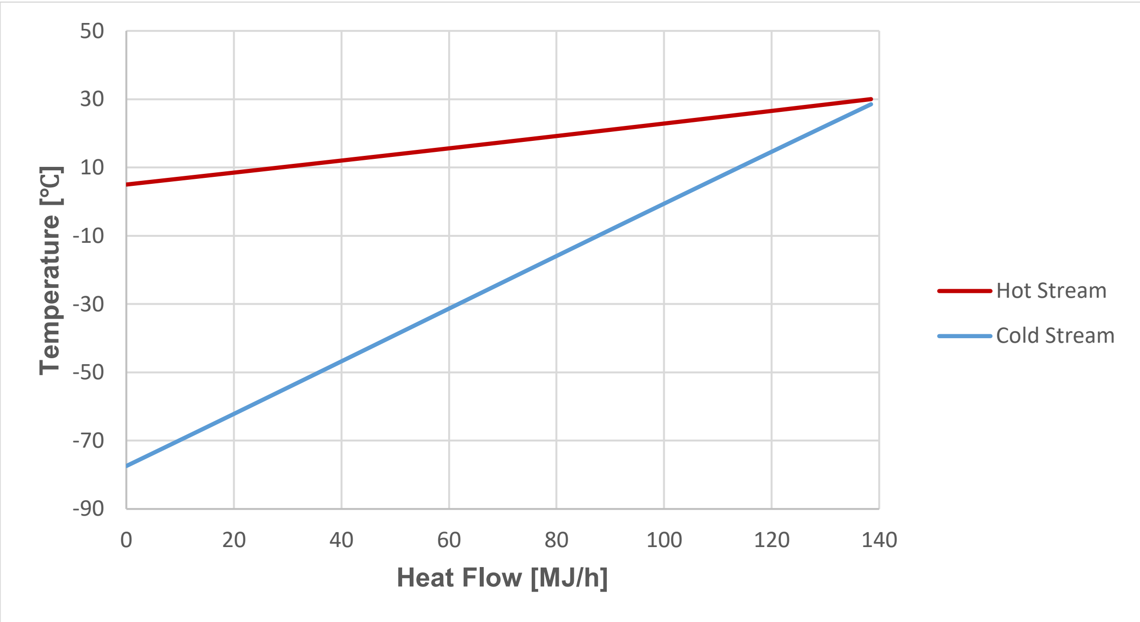

Figure 12: Mean Temperature Difference in Heat Exchanger HE-1

[58] GOST 5542-2014 "Natural Fuel Gases for Commercial and Domestic Use. Specifications"

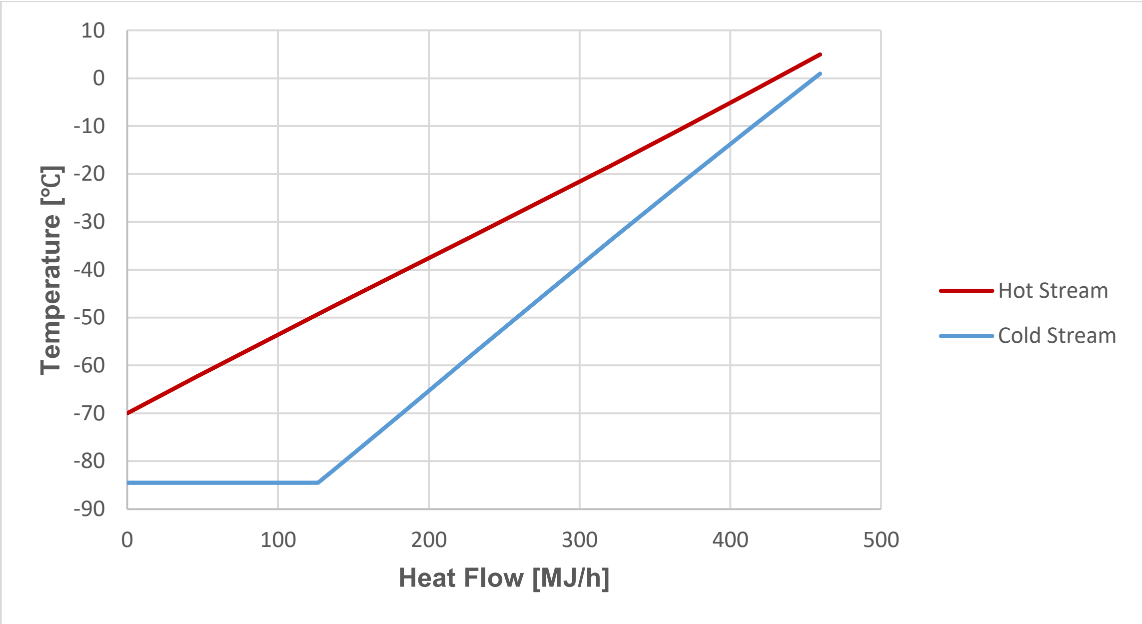

Figure 13: Mean Temperature Difference in Heat Exchanger HE-2

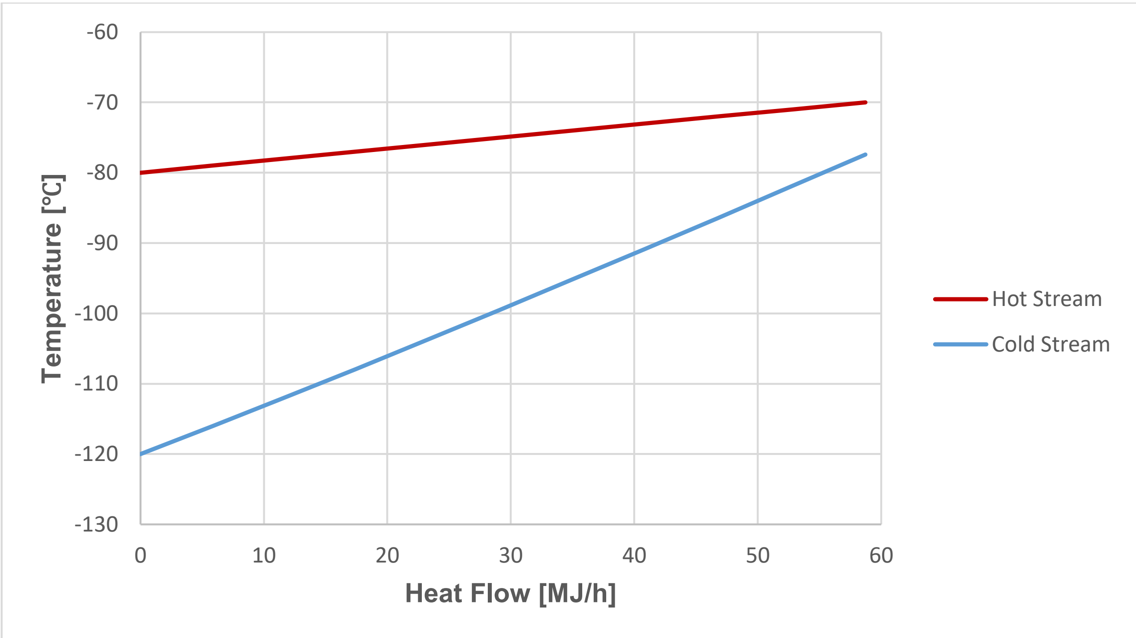

Figure 14: Mean Temperature Difference in Heat Exchanger HE-3

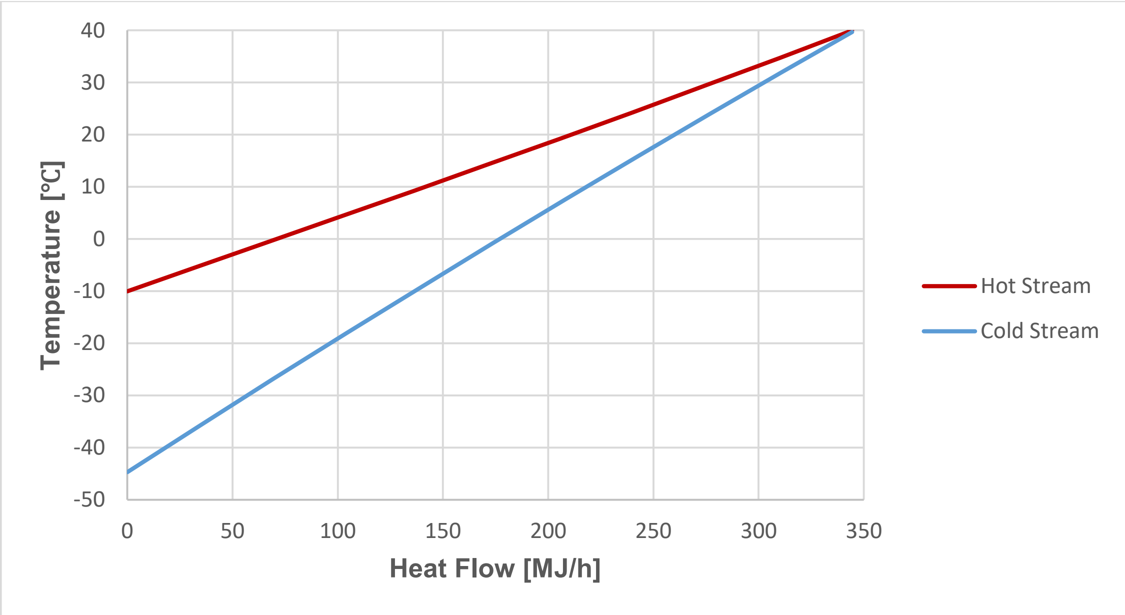

Figure 15: Mean Temperature Difference in Heat Exchanger HE-4

In all heat exchangers, flow pattern of heat-transfer mediums is parallel flow, that is, they both move in the same direction.

Plots for HE-1, HE-3 and HE-4 show that during heat transfer both fluids do not change their state of aggregation, whereas there is a change of phases in heat exchanger HE-2, namely liquid part of gas-liquid refrigerant evaporates at a constant temperature of minus 84.5 ℃, as evidenced by line that is parallel to the x-axis. As for the main gas flow in this heat exchanger, instantaneous condensation of the entire volume of feed gas occurs under specified conditions.

The exchanged heat is calculated as shown in Eq.3[59] in case there is no change of state

$$Q = k \cdot F \cdot LMTD = c_p \cdot G \cdot (t_1' - t_2'') \quad \text{(Eq. 3)}$$

Where Q is the exchanged heat (W), *k* is the heat transfer coefficient (W/m^2/C), *F* is the exchange area (m^2), *LMTD* is the logarithmic temperature difference (℃), c_p is the mass heat capacity (J/kg/C), *G* is the mass flow (kg/h), t_1' and t_2' are initial and final temperatures of heat transfer fluid respectively (℃).

If there is a change of state (e.g. evaporation or condensation), the exchanged heat is calculated as shown in Eq.4[59]

$$Q = k \cdot F \cdot LMTD = r \cdot G \quad \text{(Eq. 4)}$$

[59] Thulukkanam K. (2013), Heat Exchanger Design Handbook, Taylor & Francis Group, LLC, p. 1272

Where r is the mass heat of vaporization (kJ/kg).

The exchange area is calculated as shown in Eq. 5

$$F = \frac{Q}{k \cdot LMTD} \quad \text{(Eq. 5)}$$

Mass heat of vaporization is calculated as shown in Eq. 6[60]

$$r = H_v - H_l \quad \text{(Eq. 6)}$$

Where H_v is the vapor mass enthalpy (kJ/kg), H_l is the liquid mass enthalpy (kJ/kg).

Table 9: Initial Data for Heat Exchangers without a Change of State

Parameter	**HE-1**	**HE-3**	**HE-4**
Heat transfer coefficient, *k,* [W/m^2/C]	250	250	250
Mass flow, *G,* [kg/h]	1553	1553	5889
Mass heat capacity, c_p, [J/kg/C]	3606	3787	1051
Logarithmic temperature difference, *LMTD* [°C]	25.03	19.46	8.38
Initial temperature of heat transfer fluid, t_1' [°C]	40	-70	40
Final temperature of heat transfer fluid, t_2' [°C]	5	-80	-10

Table 10: Initial Data for Heat Exchanger with a Change of State

Parameter	**HE-2**
Heat transfer coefficient, *k,* [W/m^2/C]	900
Mass flow, *G,* [kg/h]	1553
Logarithmic temperature difference, *LMTD* [°C]	15.2

According to Eq. 3 and table 9 exchanged heat for HE-1

$$Q_{HE-1} = \frac{1553 \cdot 3606 \cdot (40 - 5)}{3600} = 38890\ W$$

[60] Lashutina N. G., Makashova O. V, (1988), Technical Thermodynamics with the Basics of Heat Transfer and Hydraulics, Leningrad “Mashinostroenie”, p. 337

Exchange area of heat exchanger HE-1 according to Eq. 5

$$F_{HE-1} = \frac{38890}{250 \cdot 25.03} = 6.2\ m^2$$

In a similar fashion, exchange areas for heat exchanger HE-3 and HE-4 are calculated and presented in table 10.

Based on simulation data provided by HYSYS

$$H_v = -4819\ kJ/kg$$

$$H_l = -5115\ kJ/kg$$

Mass heat of vaporization according to Eq. 6

$$r = (-4819) - (-5115) = 296\ kJ/kg$$

According to Eq. 3 and table 9 exchanged heat for HE-2

$$Q_{HE-2} = \frac{296000 \cdot 1553}{3600} = 127691\ W$$

Exchange area of heat exchanger HE-2 according to Eq. 5

$$F_{HE-1} = \frac{127691}{900 \cdot 15.2} = 9.5\ m^2$$

All results are collated in table 11.

Table 11: Results of Exchange Areas Calculation

Heat exchanger	**Exchange Area, [m^2]**
HE-1	6.2
HE-2	9.5
HE-3	3.4
HE-4	49

All calculated exchange areas are relatively small because of small scale of LNG production. In this system, heat exchangers HE-2 and HE-3 are interrelated, and they share the thermal duty between each other. It means that if we reduce the exchange area of the former, we will have to increase the exchanger area of the latter, and the other way around.

5.1.6 Disadvantages and Possible Solutions

Based on the analysis of simulated original scheme, the following obvious disadvantages can be identified:

1. At the specified temperatures and pressure of 20 MPa, phase transition from the gas phase to the liquid phase occurs after HE-2. This makes subsequent stages of cooling, liquefaction and stabilization ineffective (despite the fact that condensation of gas stream should occur at minus 120 ℃ after the throttle). In this case, enthalpy is spent on additional supercooling of the liquid instead of being used fruitfully
2. There is only partial condensation of refrigerant (R-14) in refrigeration circuit. As a result, the HE-2 heat exchanger receives a gas-liquid mixture consisting of only 20% of the liquid phase. This makes the cooling process even more inefficient
3. Poor quality of LNG

To eliminate these disadvantages, it is reasonable to consider the following possible solutions:

1. Consider the possibility of using this liquefaction plant downstream of a complex gas treatment unit (CGTU). This solution involves the raw gas offtake from a certain gas treating stage of CGTU and its liquefaction to produce not only LNG, but also LPG. It will help to diversify the product of CNG station and provide a sales market with gas motor fuel directly near gas field
2. Replace throttle VLV-1 with an expander. It will make the liquefaction process more efficient and at the same time impose restrictions on thermal regime upstream of the expander, since the expander normal operation requires the absence of the liquid phase at its inlet
3. Achieve separation of the liquid phase from the gas phase with step-by-step throttling by means of fractionation to increase the efficiency of the throttling process. As a result, enthalpy will be spent on condensing the gas stream and cooling the condensed liquid
4. Utilize part of produced LNG to cool feed gas. This will help to disable refrigeration circuits, thereby ensuring the self-sufficiency of the scheme and maximizing the use of free cold of several streams. These circuits will only be necessary during commissioning

It is planned to implement proposed solutions by means of pressure changes in the main line of natural gas and temperatures changes in the main heat exchangers.

As a result of this research work, it is expected to get a more energy-efficient liquefaction unit.

5.2 Liquefaction Plant Downstream of a CGTU

In this case, it is assumed to take raw gas after the first stage of separation near gas field with composition shown in table 12. In addition, it is important to mention that there is a possibility to use this liquefaction unit for associated gas after the first stage of separation since it has relatively high amount of methane and light components.

Initial parameters of this gas are as follows: temperature equals plus 10℃ and pressure is 5 MPa. Mass flow is the same as in 5.1.1.

Table 12: Raw Gas Composition

Component	**Mole Fraction**
Methane	0.8084
Ethane	0.1175
Propane	0.0533
n-Butane	0.0078
i-Butane	0.0085
n-Pentane	0.0012
i-Pentane	0.0017
n-Hexane	0.0009
n-Heptane	0.0005
n-Octane	0.0002

Process flow diagram of liquefaction plant downstream of a CGTU is depicted in figure 16.

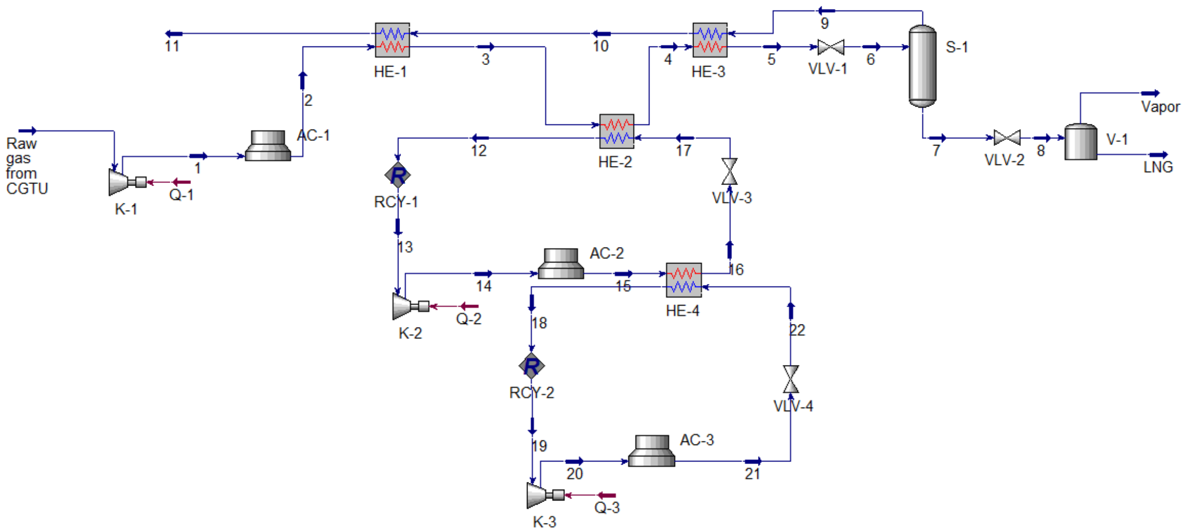

Figure 16: Process Flow Diagram of the Liquefaction Plant Downstream of a CGTU

Technological process is identical to that described in section 5.1.1. However, at the specified gas composition and pressure of 20 MPa, liquid phase comes out at plus 20℃. In order to obtain approximately the same amount of LNG as in the original scheme, it is necessary to change the main parameters. The best option according to Aspen HYSYS calculations corresponds to a pressure in the main line of 10 MPa, while temperatures after the heat exchangers HE-1, HE-2, and HE-3 are plus 30℃, minus 20℃ and minus 29℃, respectively. However, even in this case, condensation after the heat exchanger HE-2 is inevitable. As a result, a product after the tank V-1 does not conform to any of the grades specified in GOST

R 56021-2014 "Liquefied natural gas. Fuel for internal-combustion engine and generating unit. Specifications". Composition of the product is shown in the table 13.

Table 13: Product Composition

Component	Mole Fraction
Methane	0.1226
Ethane	0.4244
Propane	0.3155
n-Butane	0.0493
i-Butane	0.0548
n-Pentane	0.0089
i-Pentane	0.0119
n-Hexane	0.0061
n-Heptane	0.0047
n-Octane	0.0018

All streams with their major physical properties are presented in tables 14, 15, and 16.

Table 14: Streams of the Main Line with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
Raw gas	1	5	10	2070
1	1	10	67.6	2070
2	1	10	40	2070
3	1	10	30	2070
4	1	10	-20	2070
5	1	10	-29	2070
6	0.822	1	-84.46	2070
7	0	1	-84.46	687
8	0.1301	0.4	-97.05	687
LNG	0	0.4	-97.05	638.8
Vapor	1	0.4	-97.05	48.23
9	1	1	-84.46	1383
10	1	1	-62.5	1383
11	1	1	-37.83	1383

Table 15: Streams of the First Refrigeration Circuit with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
12	1	1	-5.48	5889
13	1	1	-5.48	5889
14	1	15	156.2	5889

15	1	15	40	5889
16	1	15	-10	5889
17	0.79	1	-84.5	5889

Table 16: Streams of the Second Refrigeration Circuit with Major Physical Indicators

Stream	**Vapor Phase**	**Pressure, [MPa]**	**Temperature, [℃]**	**Mass flow, [kg/h]**
18	1	1	39.7	5889
19	1	1	39.7	5889
20	1	15	209.3	5889
21	1	15	30	5889
22	1	1	-44.7	5889

The liquefaction coefficient in this case equals to 0.31 according to Eq. 1.
Based on analysis of the first solution, it can be concluded that the original scheme without any improvement is unsuitable for considered gas composition.
Compressors' power consumption obtained during simulation is presented in table 17.

Table 17: Compressors' Power Consumption

№ of compressor	**Power, [kW]**
K-1	53.77
K-2	168.6
K-3	201.6

5.2.1 Heat Exchange Areas

Heat exchange areas of all heat exchangers are calculated as shown in section 5.1.5 according to Eq. 3 and Eq.5 since there is no condensation in HE-2 because of different temperatures. Initial parameters for the calculation and results are presented in table 18 and table 19, respectively.

Table 18: Initial Data for Heat Exchangers

Parameter	**HE-1**	**HE-2**	**HE-3**	**HE-4**
Heat transfer coefficient, *k,* [W/m^2/C]	250	250	250	250
Mass flow, *G,* [kg/h]	2070	2070	2070	5889
Mass heat capacity, c_p, [J/kg/C]	3150	4320	5440	1051
Logarithmic temperature difference, *LMTD* [℃]	102.4	56.02	66.82	8.38
Initial temperature of heat transfer fluid, t_1' [℃]	40	30	-20	40
Final temperature of heat transfer fluid, t_2' [℃]	30	-20	-25	-10

Table 19: Results of Exchange Areas Calculation

Heat exchanger	**Exchange Area, [m^2]**
HE-1	0.9
HE-2	8.86
HE-3	1.01
HE-4	49

As it can be seen, heat exchange areas in HE-1 and HE-3 have changed drastically in comparison with results in table 11. It happened because the load on those heat exchangers decreased as well.

5.3 Expander Cycle

Classic solution for modernizing a gas liquefaction plant is to install an expander as it improves throttling. The process flow diagram of liquefaction plant with the expander is shown in figure 17.

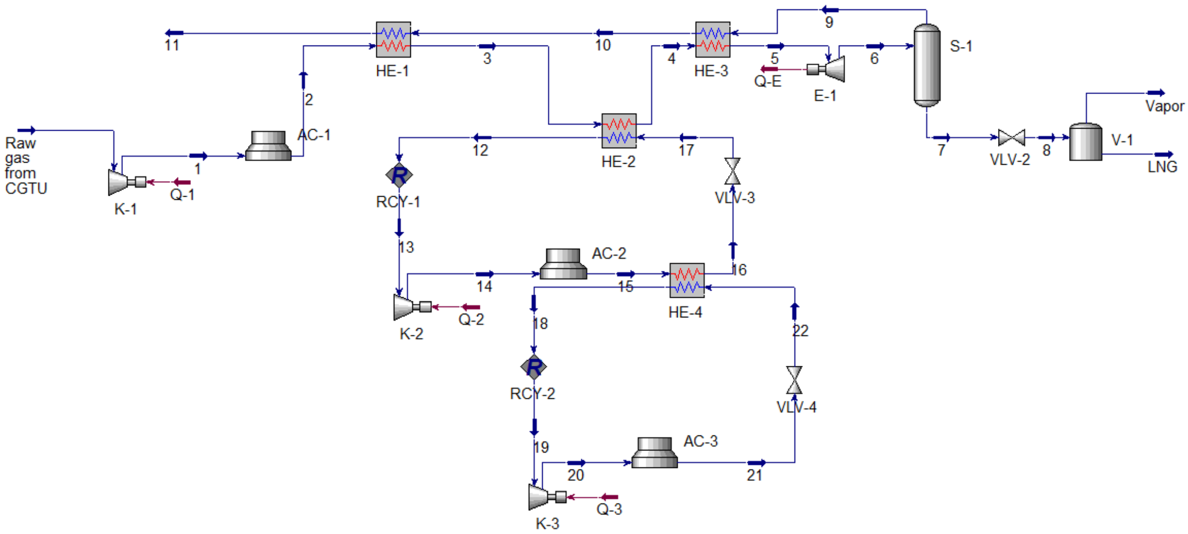

Figure 17: Process Flow Diagram of the Expander Cycle

The only difference of this solution in terms of equipment is the presence of an expander in the main line instead of the VLV-1. Thus, technological process described in paragraph 5.1.1 is fully suitable for describing this scheme. The exceptions are temperature regime and pressure in the main line, since the presence of the expander in the unit does not allow the presence of a liquid phase at its inlet. Thus, based on the calculations of Aspen HYSYS, the best option is to reduce pressure in the main line by half, that is, after the compressor K-1, feed gas enters the air cooling unit AC-1 at a pressure of 10 MPa. This pressure allows setting the following temperatures after the heat exchangers HE-1, HE-2, and HE-3: plus 30℃, minus 20℃, and minus 29℃. All streams with their major physical properties are presented in tables 20-22.

Table 20: Streams of the Main Line with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
Raw gas	1	5	10	2070
1	1	10	67.6	2070
2	1	10	40	2070
3	1	10	30	2070
4	1	10	-20	2070
5	1	10	-29	2070
6	0.3827	1	-99.65	2070
7	0	1	-99.65	874.3
8	0.1783	0.4	-115.8	874.3
LNG	0	0.4	-115.8	797.1
Vapor	1	0.4	-115.8	77.16
9	1	1	-99.65	1195
10	1	1	-79.48	1195
11	1	1	-55.60	1195

Table 21: Streams of the First Refrigeration Circuit with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
12	1	1	-5.48	5889
13	1	1	-5.48	5889
14	1	15	156.2	5889
15	1	15	40	5889
16	1	15	-10	5889
17	0.79	1	-84.5	5889

Table 22: Streams of the Second Refrigeration Circuit with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
18	1	1	39.7	5889
19	1	1	39.7	5889
20	1	15	209.3	5889
21	1	15	30	5889
22	1	1	-44.7	5889

The liquefaction coefficient in this case equals to 0.38 according to Eq. 1.
Based on analysis of this solution, it can be concluded that the expander cycle works a little bit better as opposed to the original scheme in terms of LNG quality and liquefaction coefficient. However, these indicators are still pretty low for real operation.
Power consumption of rotating equipment obtained during simulation is presented in table 23.

Table 23: Power Consumption of Rotating Equipment

№ of rotating equipment	Power, [kW]
K-1	53.77
K-2	168.4
K-3	201.6
E-1	42.45

5.3.1 Heat Exchange Areas

In this case, heat exchange areas are all the same as in previous section (table 24) because there is no change in input parameters.

Table 24: Results of Exchange Areas Calculation

Heat exchanger	Exchange Area, [m^2]
HE-1	0.9
HE-2	8.86
HE-3	1.01
HE-4	49

5.4 Fractionation

Since the raw gas contains heavy hydrocarbons with higher boiling points, it is difficult to use very low temperatures necessary for gas liquefaction. Therefore, this solution involves the use of rectification columns installed before the liquefaction installation.

The process of separating components goes as follows. Feed gas moves up the column at a temperature higher than that of the liquid flowing counter-flow to the gas. As a result of interaction between two phases, the liquid partially evaporates, while mainly light components pass into the gas. Evaporation of the liquid at the point of contact occurs due to the heat of gas condensation. Mainly heavy components condense from the gas. Thus, as the gas moves up, it becomes more and more saturated with light components. Reflux liquid consists mainly of light components at the top of the column, but as it moves down, it saturates with heavy components that condense from gas.

In this case, two columns are used. One of them serves to stabilize a product coming out of the first column. This is necessary because after the first column, a product is unstable at a relatively high pressure and its decrease may lead to evaporation of light components. Since the stabilization column has a high efficiency of hydrocarbon mixture separation, it eliminates a loss of liquid light components and allows obtaining a stable output in the form of LPG what reduces a loss of a valuable product during further operations. Main parameters of both columns are presented in table 25.

Table 25: Input Parameters of Columns

Parameter	**Column T-1**	**Column T-2**
Condenser pressure, [MPa]	2.9	1.59
Reboiler pressure, [MPa]	3	1.6
Inlet stage/Number of stages	6/10	6/10
Temperature up, [℃]	-68	-10
Temperature down, [℃]	1	45

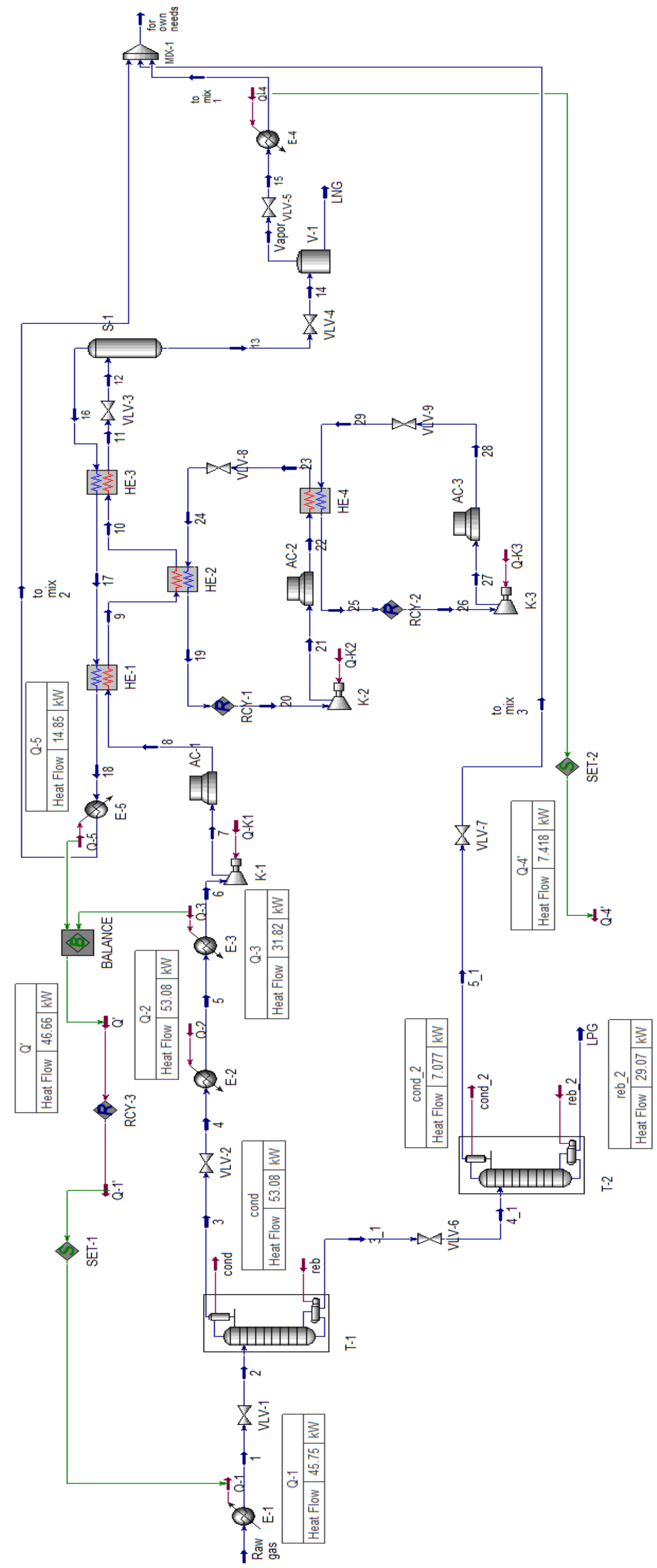

Figure 18: Process Flow Diagram of Original Scheme with Fractionation

The technological process is carried out as follows. Feed gas (stream Raw gas) enters a multipass heat exchanger where it is cooled to minus 12.46℃. On the process flow diagram, this heat exchanger is represented as combined cooler E-1 and heaters E-3 and E-5. Their heat flow balance is converged. In the throttle VLV-1, feed gas' pressure drops to 3 MPa (stream 2). After that, the gas flow enters a column T-1. In the column, it is divided into a gaseous stream 3 with a temperature of minus 68℃ and a pressure of 2.9 MPa and a condensate stream 3_1 with a temperature of plus 1℃ degree and a pressure of 3 MPa.

The condensate stream after throttling in VLV-6 to a pressure of 1.6 MPa (stream 4_1) is directed to a stabilization column T-2. At the outlet of the column (stream LPG), liquid product composition (table 26) corresponds to autogas in accordance with GOST R 52087-2018 "Fuel liquefied hydrocarbon gases. Specifications"[61]. Gaseous phase (stream 5_1) passes through a throttle VLV-7 and is sent to be mixed with other gases for own needs (stream to mix 3).

Partial condensation occurs in condenser at the expense of cold gas (stream 4 for column T-1 and stream 15 for column T-2). It should be mentioned that this cold might be spread across the highest point of column and inlet stage.

Table 26: LPG Composition after Column T-2

Component	**Mass Fraction**
Methane	0.0000
Ethane	0.0541
Propane	0.7593
n-Butane	0.1527
n-Pentane	0.0340

The gaseous stream after T-1 (stream 3) passes a throttle VLV-2 and multipass heat exchanger (E-1, E-3, E-5) at a pressure of 2 MPa and a temperature of plus 5℃ it goes to a the compressor K-1 suction line. Further technological process is identical to that described in paragraph 5.1.1 with the only difference: pressure in the main line is lowered to 10 MPa, and temperatures after the heat exchangers HE-1, HE-2, and HE-3 are plus 20℃, minus 75℃ and minus 80℃, respectively. In the tank V-1, liquefied natural gas composition (table 27) corresponds to grade B according to GOST R 56021-2014 "Liquefied natural gas. Fuel for internal-combustion engine and generating unit. Specifications". Gaseous phase coming out of the V-1 (stream Vapor) goes through throttle VLV-5 and uses its cold in column T-2.

[61] GOST R 52087-2018 "Fuel Liquefied Hydrocarbon Gases. Specifications".

Table 27: LNG Composition

Component	Mole Fraction
Methane	0.8185
Ethane	0.1782
Propane	0.0033

It is also proposed to mix the gaseous phase (stream 16) coming from the separator S-1 and heated to plus 5℃ in the heat exchangers HE-3, HE-1 and E-102 (stream to mix 2) with vapor leaving the tank V-1. The resulting gas consisting for the most part of methane (table 28) can be used for own needs or injected into main pipeline.

Table 28: Composition of Mixed Gas for Own Needs

Component	Mole Fraction
Methane	0.9142
Ethane	0.0703
Propane	0.0154

The rest of the streams are presented in tables 29-31 along with their physical properties.

Table 29: Streams of the Main Line with Major Physical Indicators

Stream	Vapor Phase	Pressure, [MPa]	Temperature, [℃]	Mass flow, [kg/h]
Raw gas	1	5	10	2070
1	1	5	-12.46	2070
2	0.95	3	-25.08	2070
3	1	2.9	-68	1565
4	1	2	-76.44	1565
5	1	2	-27.19	1565
6	1	2	5	1565
7	1	10	150	1565
8	1	10	40	1565
9	1	10	20	1565
10	0	10	-75	1565
11	0	10	-80	1565
12	0.42	1	-120	1565
13	1	1	-120	953
14	0.12	0.5	-134.3	953
LNG	0	0.5	-134.3	851.8
Vapor	1	0.5	-134.3	101.2
To mix 1	1	0.2	-15	101.2

15	1	0.2	-139.5	101.2
16	1	1	-120	612
17	1	1	-102.9	612
18	1	1	-33.93	612
To mix 2	1	1	5	612
3_1	0	3	1.044	425.8
4_1	0.16	1.6	-11.52	425.8
5_1	1	1.59	-10.02	160
To mix 3	1	0.2	-30.55	160
LPG	0	1.6	45	265.8
For own needs	1	0.2	-6.1	873.2

Table 30: Streams of the First Refrigeration Circuit with Major Physical Indicators

Stream	**Vapor Phase**	**Pressure, [MPa]**	**Temperature, [℃]**	**Mass flow, [kg/h]**
19	1	1.2	-7.84	7853
20	1	1.2	-7.84	7853
21	1	25	176.5	7853
22	1	25	40	7853
23	1	25	-20	7853
24	0	1.2	-79.8	7853

Table 31: Streams of the Second Refrigeration Circuit with Major Physical Indicators

Stream	**Vapor Phase**	**Pressure, [MPa]**	**Temperature, [℃]**	**Mass flow, [kg/h]**
25	1	1	39	7853
26	1	1	39	7853
27	1	15	208.5	7853
28	1	15	25	7853
29	1	1	-53.47	7853

The liquefaction coefficient in this case equals to 0.41 according to Eq. 1.
Compressors' power consumption obtained during simulation is presented in table 32.

Table 32: Compressors' Power Consumption

№ of compressor	**Power, [kW]**
K-1	117.3
K-2	257.6
K-3	268.1

In this case, at given conditions gas turns into liquid phase after heat exchanger HE-2 as it does in the original scheme. However, minor changes in the refrigerant circuit made it possible to liquefy the entire refrigerant after VLV-8.

The main columns' characteristics are depicted in figures 19-26.

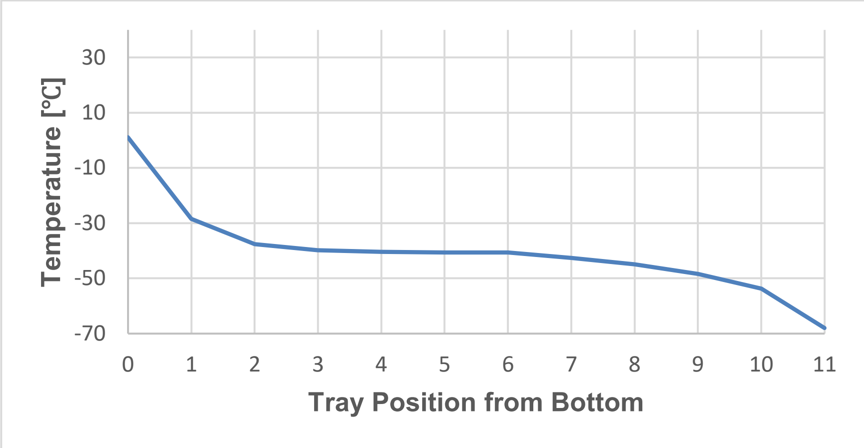

Figure 19: Temperature Performance along the Column T-1

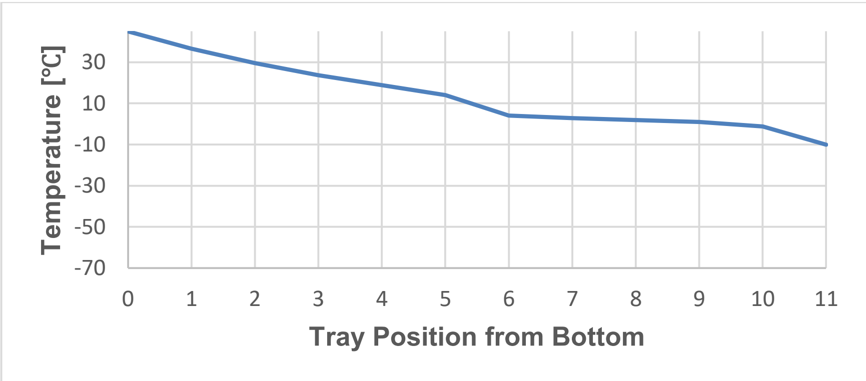

Figure 20: Temperature Performance along the Column T-2

Figures 19-20 represent temperature profiles along the columns. The gas stream cools as it goes up inside the columns because of heat exchange with condensate that goes down at a lower temperature. The plateau between third and sixth trays in figure 19 means that there is no mass transfer between gas and condensate stream in this section.

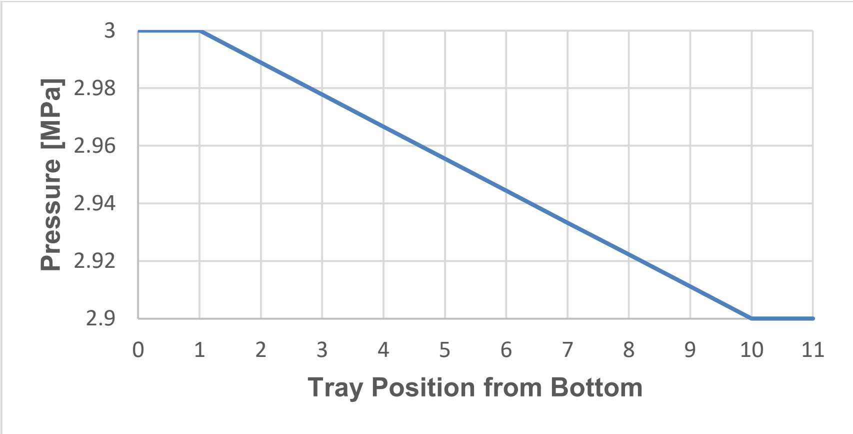

Figure 21: Pressure Performance along the Column T-1

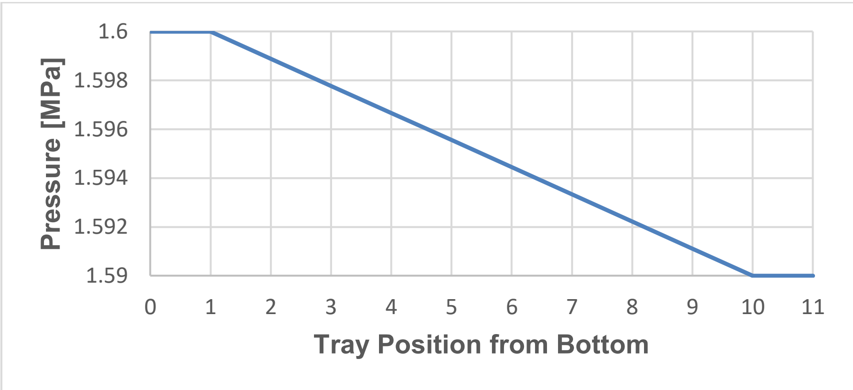

Figure 22: Pressure Performance along the Column T-2

In figures 21-22, we can observe pressure profile along the columns. There is a pressure drop of 0.1 MPa from bottom to top of the columns that was set manually at a design stage. This pressure drop may be less but 0.1 MPa works well for this case study.

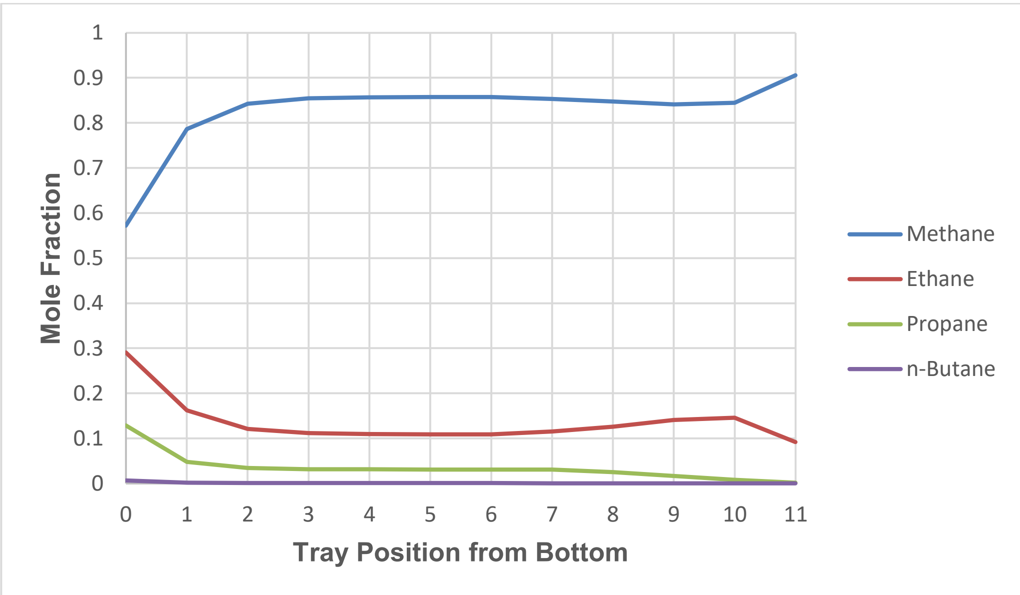

Figure 23: Mole Fraction of Vapor Components along the Column T-1

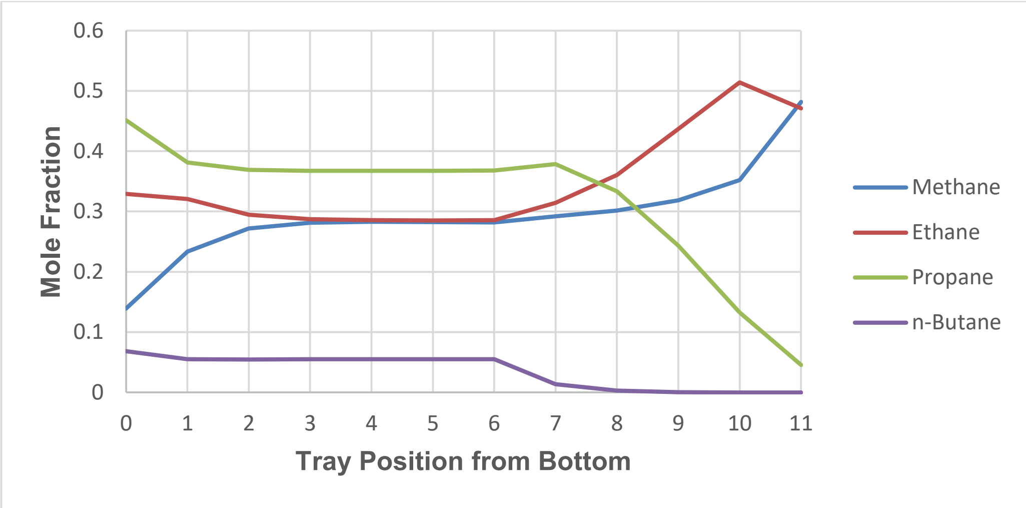

Figure 24: Mole Fraction of Liquid Components along the Column T-1

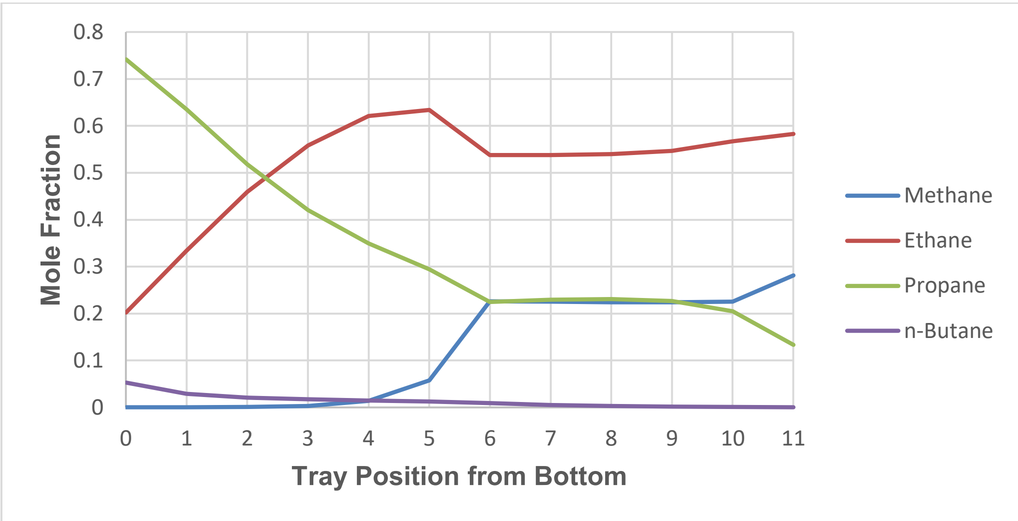

Figure 25: Mole Fraction of Vapor Components along the Column T-2

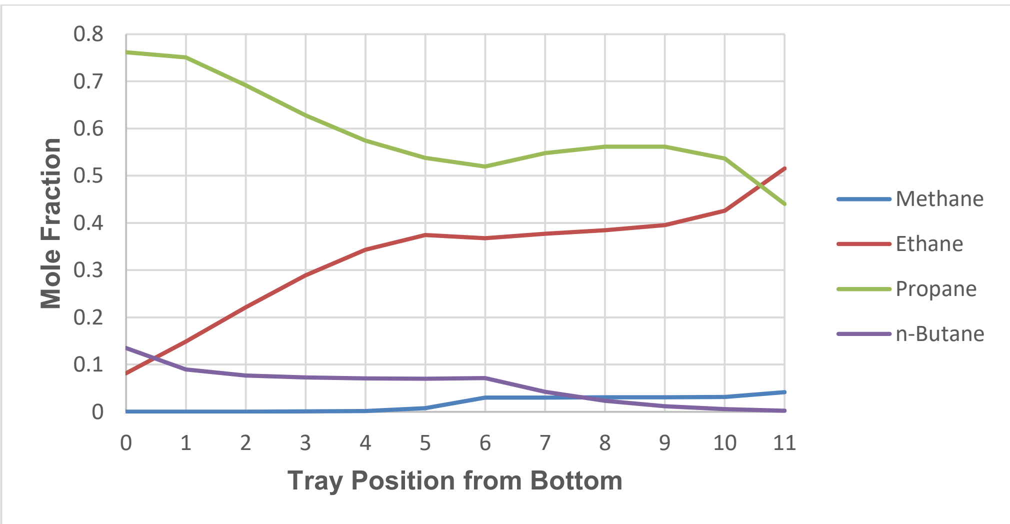

Figure 26: Mole Fraction of Liquid Components along the Column T-2

Vapor and liquid components along the columns are shown in figures 23-26. In column T-1, the gas stream saturates with methane as it reaches an eleventh tray (figure 23). At the same time mole fraction of propane in liquid phase goes up as it moves down from the top of the column (figure 24). Meanwhile, the liquid releases lighter fractions due to temperature increase. In column T-2 (figures 25-26), this process is more demonstrable because T-2 is a stabilization column and inlet stage is more distinct.

5.4.1 Heat Exchange Areas

Since in this case condensation occurs after HE-2, heat exchange area is calculated according to Eq. 4-6, whereas for HE-1, HE-3, and HE-4 according to Eq. 3 and Eq. 5. Initial parameters for the calculation and results are presented in tables 33 and 34, respectively.

Table 33: Initial Data for Heat Exchangers without a Change of State

Parameter	**HE-1**	**HE-3**	**HE-4**
Heat transfer coefficient, *k,* [W/m^2/C]	250	250	250
Mass flow, *G,* [kg/h]	1565	1565	7853
Mass heat capacity, c_p, [J/kg/C]	3050	4625	1045
Logarithmic temperature difference, *LMTD* [℃]	94.46	33.65	8.38
Initial temperature of heat transfer fluid, t_1' [℃]	40	-75	40
Final temperature of heat transfer fluid, t_2' [℃]	20	-80	-20

Table 34: Initial Data for Heat Exchanger with a Change of State

Parameter	**HE-2**
Heat transfer coefficient, *k,* [W/m^2/C]	900
Mass flow, *G,* [kg/h]	1565
Vapor mass enthalpy, H_v, [kg/h]	4952
Liquid mass enthalpy, H_l, [kg/h]	4515
Logarithmic temperature difference, *LMTD* [℃]	22.91

Table 35: Results of Exchange Areas Calculation

Heat exchanger	**Exchange Area, [m^2]**
HE-1	1.12
HE-2	9.21
HE-3	1.19
HE-4	65.1

Table 35 shows that other than drastic reduction in heat exchange areas in HE-1 and HE-2, there is an increase in heat exchange area of HE-4. It is related to change of mass flow in refrigeration circuit.

5.5 Cooling Feed Gas with the Part of Produced LNG Flow

After analyzing all simulated schemes, it turns out it is not possible to use part of produced LNG flow for cooling natural gas.

In the original scheme, this solution is impractical because the output will be sharply reduced. Accordingly, its use in the expander cycle is also impossible. As for the solution with fractionation before the liquefaction unit, there is no way to use part of produced LNG flow to cool natural gas due to lack of free cold, which enabled the operation of the columns T-1 and T-2.

5.6 Approximate Economic Evaluation

Since possible solutions described in sections 5.2 and 5.3 do not comply with requirements for quality of produced LNG, it is reasonable to evaluate only original scheme and scheme with fractionation described in section 5.4 (hereinafter referred to as modernized scheme).

Estimated specific energy consumption of liquefaction plant is calculated as shown in Eq. 7

$$E = \frac{P}{G} \qquad \text{(Eq. 7)}$$

Where *E* is estimated specific energy consumption of liquefaction plant (kWh/ton), *P* is total power consumption (kW) and *G* is mass flow of produced LNG (ton/h).

Estimated cost of LNG production per year is calculated as shown in Eq. 8

$$C = s \cdot G \cdot T \cdot E \qquad \text{(Eq. 8)}$$

Where *C* is estimated cost of LNG production per year ($), *s* is the average cost of 1 kWh (0.15$), *G* is mass flow of produced LNG (ton/h), *T* is a number of working hours per year without workovers and commissioning operations (8400 h) and *E* is estimated specific energy consumption of the liquefaction plant (kWh/ton).

According to tables 5 and 8 and Eq. 7 specific energy consumption in the original scheme equals to

$$E = \frac{(115.6 + 173.3 + 201.6)}{0.8054} = 609\ kW \cdot h/ton$$

Estimated cost of LNG production per year for the original scheme

$$C_o = 0.15 \cdot 0.8054 \cdot 8400 \cdot 609 = 618{,}030\ \$$$

The same calculations are made for the scheme with columns in accordance with data in tables 29 and 32 and results are collated in table 36.

Table 36: Specific Energy Consumption and Estimated Cost of LNG for the Modernized Scheme

Parameter	**Value**
Estimated specific energy consumption, *E*, [kWh/ton]	755
Estimated cost of LNG production per year, C_c, [$]	810,180

As it can be seen, estimated cost of LNG production per year is increased by 192,150$ after modernization.

There are also going to be additional costs for new facilities such as columns and the heat exchanger. It is assumed to neglect the valves costs because they are relatively small. Rough installation costs are presented in table in accordance with Aspen HYSYS Economics.

Table 37: Costs of Additional Equipment

Equipment	**Cost, [$]**
Column T-1	340,100
Column T-2	244,700
Multipass heat exchanger	167,100
Total	**751,900**

Estimated annual revenue from LNG and LPG production is calculated as shown in Eq. 9

$$R = T \cdot (Q \cdot p_{LNG} + G \cdot p_{LPG}) \qquad \text{(Eq. 9)}$$

Where *R* is the annual revenue ($), *T* is a number of working hours per year without workovers and commissioning operations (8400 h), *Q* is the molar flow of produced LNG (1022 m^3/h), p_{LNG} is the average market price of LNG (180$/1000 m^3), *G* is the mass flow of produced LPG (265.8 kg/h) and p_{LPG} is the average market price of LPG (240$/ton).

Estimated annual revenue from LNG and LPG production according Eq. 9

$$R_c = 8400 \cdot \frac{(1022 \cdot 180 + 265.8 \cdot 240)}{1000} = 2{,}081{,}117\$$$

Molar flow of produced LNG in the original scheme is 1065 m^3/h and the average market price of LNG 150$/1000 m^3.

Estimated annual revenue from LNG production in the original scheme according Eq. 9

$$R_o = 8400 \cdot \frac{(1065 \cdot 150 + 0)}{1000} = 1{,}341{,}900\$$$

Estimated real revenue in the first year of the modernized scheme operation is calculated as shown in Eq. 10

$$R_{real} = R_c - C_c - X \qquad \text{(Eq. 10)}$$

Where *X* is a total cost of additional equipment ($).

$$R_{real} = 2{,}081{,}117 - 810{,}180 - 751{,}900 = 519{,}037\$$$

In the second year of the modernized scheme operation estimated real revenue is calculated in the same way as for the original scheme in Eq. 11

$$R_{real} = R - C \qquad \text{(Eq. 11)}$$

Estimated real revenue in the second year of the modernized scheme operation

$$R_{real} = 2{,}081{,}117 - 810{,}180 = 1{,}270{,}937\$$$

The rest of the results for several years ahead are presented in table 38.

Table 38: Real Annual Revenue of Both Schemes

Year of Operation	First year, [$]	Second year, [$]	Sum, [$]
Original Scheme	723,870	723,870	1,447,740
Modernized Scheme	519,037	1,270,937	1,789,944

After analyzing data presented in table 38, it can be concluded that by the end of the second year of operation, the modernized scheme will have recovered additional expenses.

6 Conclusion and Recommendations

6.1 Conclusion

The main conclusion of the thesis can be summarized in the following points:

1. Conclusions of market and technology analysis:
   - Gas motor fuel is extremely important for the development of Russian economy due to its price competitiveness in comparison with other types of fuel and growing technologies
   - Conversion to gas motor fuel is required not only for automobile, but also for water and rail transport
   - The main factor that delays the development of gas motor fuel market is a weak infrastructure of gas filling stations. It is also required to take into account the psychological unpreparedness of consumers and the presence of unreasonable psychological misconceptions and stereotypes
   - Rapid gas motor fuel promotion is critically connected with the governmental support measures, planning and implementation of state support programs and creation of a refuelling infrastructure
2. Case study conclusions:
   - At the specified composition, temperatures and pressure the original liquefaction unit does not work that effectively due to early condensation of feed gas in the main line, which makes the further process even more ineffective. It entails a big drop in produced LNG quality
   - After relocating the liquefaction unit to a complex gas treatment unit, the situation came out to be even worse. Since heavy hydrocarbons were present in the feed gas, condensation occurred at higher temperatures. It has deteriorated LNG output in terms of composition and quantity, which means that this type of scheme has no ability to adapt to changes in the composition of feed gas
   - Classical way of improving liquefaction plant efficiency by using an expander is not suitable in this case. Although results of modeling were better than those of the original scheme with new gas composition due to enhanced throttling, they were still not sufficient to comply with the requirements. At a given conditions a slight improvement in LNG output is negligible compared to an increase in specific energy consumption and high cost of the expander
   - Fractionation unit solved most of all mentioned problems. After two columns were added in the upstream of the liquefaction unit, it became possible not only to remove almost all heavy hydrocarbons from the gas stream but also to produce high quality LPG along with LNG. Since columns use free cold that is taken from some gas streams, they are self-sufficient. It helps saving money for their operation not using external sources. The use of fractionation unit allows producing only two types of gas motor fuels but without any complicated catalytic reactions. This makes operation process easier. In addition, there is an opportunity to sell products right

away if consumer is nearby. In this case, approximate economic evaluation shows that the expenses will be recovered in less than two years

- Cooling feed gas with the part of produced LNG is considered inefficient for the original scheme and expander cycle, while for the fractionation solution it is simply impossible due to absence of free cold

6.2 Recommendations

Based on the findings of this thesis the following recommendations can be draw:

1. It is recommended to consider using this unit for associated petroleum gas taken from the first stage of separation. In this case, the gas will have a relatively high content of methane and light hydrocarbon fractions. This means that this proposal can be further adapted at the oil treatment plant and the main oil pumping station
2. It is also recommended to consider the option of splitting these columns into the simplest elements in the form of separators and throttles, that is, to make the process stepwise. Thus, each subsequent stage will maintain a lower temperature, and the enthalpy will be spent on condensing the gas flow and cooling the condensed liquid. This will increase the efficiency of the liquefaction plant, reduce the complexity of operation and its costs

References

Aleksankov A., "Prospects for the Use of Gas Motor Fuel in Russia," Proceedings of the Saint Petersburg State University of Economics, vol. 4, p. 96-99, 2019.

Alifirova E., "Goal-Regions. Gazprom Considered the Development of the Russian Gas Motor Fuel Market," Neftegaz.RU, 2019.

Arhireev V., "Gas Motor Fuel Market in Russia: Is There Any Prospect of Moving Away from Oil?" REGNUM, News Agency, 2017. [Online]. Available: https://regnum.ru/news/economy/2275425.html

Arteconi P. F., "LNG as Vehicle Fuel and the Problem of Supply: The Italian Case Study," p. 503-512, 2016.

Aspen HYSYS V8.8 Help.

Baikov N. M., Saifeev M. A. (1974). Production and Use of Liquefied Gases Abroad (Review of Foreign Literature). Moscow: VNIIOENG

Bronfenbrenner, J. C. (2008). On a Small-Scale. LNG Industry

Cheminava B.T., Kondratenko S.E. (2017). Development of the Russian Gas Motor Fuel Market by Attracting Private Investments, Gas Industry № 12, p. 74-78

"CNG Filling Stations Chain," Gazprom, [Online]. Available: https://gazprom-agnks.ru/prices/.

"Coil-wound Heat Exchanger," Linde AG, 2018. [Online]. Available: https://www.linde-engineering.com/en/index.html.

Darredeau B., "Method of Cooling a Gaseous Mixture and Installation Therefor". Patent US 3780535, 1973.

Fedorova E. B., Current State and Development of the Global Liquefied Natural Gas Industry: Technologies and Equipment, Moscow: Gubkin Russian State University of Oil and Gas, 2011, p. 159.

Fedorova E. B, Melnikov V. B. (2015). Prospects for Development of Small-Scale Liquefied Natural Gas in Russia. Oil & Gas Chemistry, 44-51

"Gas Motor Fuel. Economy and climate. Information-analytical system of Recongress," 2019.

Gaydt D.D., Mishin O.L. (2015). A Method for Producing Liquefied Natural Gas and Complex for Its Implementation. Patent No. 2541360

Gorbachev S. P., Loginov A. A. (2008). Features of LNG Manufacture on Gas Distribution Stations at Variable Pressure in the Main Gas Pipelines. Transport on Alternative Fuel, p. 66-69

Gorbachev S.P., Lyugay S. V. (2015). Problems and Prospects of LNG Production at Gas Distributing Plants. Special Issue – Gas in Engines, 728, p. 45-49

Gorbachev S. P., Koposov A. I. (2008). Evaluating the Efficiency of Small-Scale LNG Production at Gas Distribution Stations. Russian Gas Industry. Current Aspects, p. 50-53

Gorbachev S. P., Medvedkov I. S. (2012). Effect of High-Boiling Components in LNG Production at GDS. Transport on Alternative Fuel, p. 48-54

Gorbachev S.P., "Peculiarities of LNG Small-Scale Production at Gas Pipelines Based upon High-Pressure Throttle Cycles," Industrial Gases, vol. 16, p. 29-36, 2016.

GOST R 56021-2014. "Liquefied Natural Gas. Fuel for Internal-combustion Engine and Generating Units. Specifications".

GOST 5542-2014 "Natural Fuel Gases for Commercial and Domestic Use. Specifications".

GOST R 52087-2018 "Fuel Liquefied Hydrocarbon Gases. Specifications".

Grachev I. D., Sharapov M. M. (2014). Gas Motor Fuel as Alternative to Traditional Sources of Consumption of Engines. Economic Analysis: Theory and Practice

Gritsenko A. I., (1999). Collection and Field Preparation of Gas in the Northern Fields of Russia. Moscow: Nedra Moscow

Grushevenko E.V, Kapustin N.O., Ryjkova V.V. (2016). System Analysis of the Gas Motor Fuel Market Development in Russia, Environmental Bulletin of Russia, p. 4-9

"In 2019, 4 Billion Rubbles of Subsidies Can Be Allocated for the Development of the Gas Motor Fuel Market," EnergyLand.info, Analytics – Oil and Gas, 2019. [Online]. Available: Retrieved from: http://www.energyland.info/analitic-show-181562.

Ishmuratova M., Russian Small-Scale LNG, Regional Series: Kuzbass, Yakutia, Far East, Sakhalin, Black Sea, Moscow: Energy Center of the Moscow School of Management SKOLKOVO, 2019, p. 54.

Kohler T., Bruentrup M. & R.D. Key, Edvardsson T. (2014). Choose the Best Refrigeration Technology for Small-Scale LNG Production. Hydrocarbon Processing, p. 45-52

Kondratenko S., "Prospects for Using Liquefied Natural Gas as a Motor Fuel in Russia," Gas Industry, vol. 4, p. 76-82, 2017.

Kondratenko, A. D. Karpov A. B., Kozlov M. A. (2016). Russian Small-Scale Production of Liquefied Natural Gas. Oil and Gas, p. 31-36

Lashutina N. G., Makashova O. V, (1988), Technical Thermodynamics with the Basics of Heat Transfer and Hydraulics, Leningrad “Mashinostroenie”, p. 337

"Liquefied Natural Gas (LNG), Liquefaction Technologies," Neftegaz.Ru: Technical Library, [Online]. Available: https://neftegaz.ru/tech-library/energoresursy-toplivo/141460-szhizhennyy-prirodnyy-gaz-spg-tekhnologii-szhizheniya/.

"Liquefied Natural Gas in Quarry Equipment Project is Presented at the International Forum by REC "Kuzbass"," Administration of Kuzbass Government, 2019. [Online]. Available: https://ako.ru/news/detail/proekt-nots-kuzbass-po-ispolzovaniyu-szhizhennogo-prirodnogo-gaza-na-karernoy-tekhnike-predstavlen-n.

"LNG Blue Corridors," [Online]. Available: www.lngbluecorridors.eu.

"LNG Blue Corridors - Across (Parts of) Europe," [Online]. Available: https://gazeo.com/up-to-date/news/2014/LNG-Blue-Corridors-across-parts-of-Europe,news,8000.html.

Lyugay S. V., "Increasing the Efficiency of Natural Gas Liquefaction at Gas Distributing Plants at Gas Main Pipelines," in Ph.D. Thesis in Engineering Science, Moscow, Gazprom VNIIGAZ LLC, 2010.

Makarova I. V., Khabibullin R. G., Gabsalikhova L. M., Valiev I. I. (2010). Prospects and Risks of Converting Motor transport to Gas Motor Fuel. p. 1209-1214

"Ministry of Energy of Russian Federation," [Online]. Available: https://minenergo.gov.ru/node/4852

Mirov B. K., "Ecological Eficiency of Application of Liquefied Hydrocarbon Gas in Road Transport," Current Issues of Technical Sciences, p. 45-47, 2019.

"Natural gas, supplied and transported via main gas pipelines. Technical conditions". STO Gazprom 089-2010.

"Natural Gas Vehicle Knowledge Base: Emissions," NGV Global, [Online]. Available: http://www.iangv.org/natural-gas-vehicles/emissions/.

Nikiforov O., "Prospects for Small-scale production: Liquefied Natural Gas Interested Not Only Large Enterprises," NG-Energy, 2018. [Online]. Available: http://www.ng.ru/energy/2018-09-10/13_7307_spg.html.

"No gas for gas, Russian gas community," [Online]. Available: https://www.gazo.ru/events/5849/.

Ogorodnikov E., "Pour Liquid Gas," Expert, 2017. [Online]. Available: http://expert.ru/expert/2017/06/zalyut-zhidkim-gazom/.

Order of the Ministry of Transport of the Russian Federation of 14.03.2008 no. AM-23-R "On the Introduction of the Guidelines" Standards of Fuel and Lubricants Consumption in Road Transport"".

Popov N. A., Belov M. B. (2011). Creating Natural Gas Liquefaction Plant and the Introduction of Effective LNG Technologies. Gas Filling Station + Alternative Fuel, p. 17-20

Price B., Mahaley M., Shimer W. Optimize Small-Scale LNG Production with Modular SMR Technology. (Gulf Publishing Holdings LLC)

Protsenko N., "Gas from the High Road," Oil capital, 2020.

Rachevsky B., Liquefied Petroleum Gases, Moscow: Oil and gas, 2009, p. 640.

Ratner S. V., "Questions of Practical Realization of the State Economic Policy in theFfield of Energy Efficiency," Economic Analysis: Theory and Practice, vol. 29, 2013.

Reid, R., Prausnitz, J., and Sherwood, T. (1982) Properties of Gases and Liquids: a Reference Guide. Chemistry. p. 592.

Romashkina M., "Development of the Gas Motor Fuel Market is Impossible without Government Support," Oil Capital, 2019.

Rudoy Y. G., "Equation of the State," Great Russian Encyclopedia, vol. 33, p. 65, 2017.

"Russian Natural Gas Liquefaction Plants," The Role of LNG in Russia's Export Strategy, p. 68-81, 2019.

Silakova V. V., "Realization of Actions for Strengthening of Ecological Safety in an Oil and Gas Complex on the Basis of Scientific and Technical Cooperation," Economic Analysis: Theory and Practice, vol. 1, 2012.

"Small-Scale LNG, 2012 – 2015 Triennium Work Report," International Gas Union, 2015.

The UN/ECE Regulation № 49. Uniform Instructions Concerning the Certification of Vehicles with Compression-ignition Engines which with Regard to the Emission of Pollutants Operate on Natural Gas.

"The Ministry of Energy Will Add Gas: the Essence of the Program for the Development of the Gas Engine Market," RBC, 2018. [Online]. Available: https://www.rbc.ru/business/26/11/2018/5bf551d19a794705c3f0d95d.

Thulukkanam K., Heat Exchanger Design Handbook, Taylor & Francis Group, LLC, 2013, p. 1272.

Tsvetkov A. V., "New Evolutionary Model of Transport and Communication Interaction between Russia and China".

Tsvigun I. V., Ershova E. V. (2016). Global LNG Market: Current Situation and Development Trends. Bulletin of Baikal State University, 26, p. 868-881

Zaikin O. A., Features of the Use of Alternative Energy and Modern Gas Cylinder Systems in Road Transport, Astrakhan: State Technical University-Astrakhan: Publishing House of AGTU, 2014, p. 340.

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Abbreviations

CAPEX	Capital Expenditure
CNG	Compressed Natural Gas
CGTU	Complex Gas Treatment Unit
CWHE	Coil-Wound Heat Exchanger
GDP	Gross Domestic Product
GDS	Gas Distributing Station
GOR	Gas-Oil Ratio
GMF	Gas Motor Fuel
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MR	Mixed Refrigerant
NGV	Natural Gas Vehicle
PR	Peng-Robinson
PRSV	Peng-Robinson-Stryjek-Vera
SMR	Single Mixed Refrigerant
SRK	Soave-Redlich-Kwong
SPIEF	Saint Petersburg International Economic Forum
SPB	Self-supporting Prismatic-shape IMO type B
UN/ECE	United Nations Economic Commission for Europe

Nomenclature

C	Estimated cost of LNG production per year [$]
c_p	Mass heat capacity [J/kg/℃]
E	Estimated specific energy consumption of liquefaction plant [kWh/ton]
F	Heat exchange area [m^2]
G	Mass flow [kg/h]
H_l	Liquid mass enthalpy [kJ/kg]
H_v	Vapor mass enthalpy [kJ/kg]
k	Heat transfer coefficient [W/m^2/℃]
K_l	Liquefaction coefficient
L	Mass flow of liquefied gas [kg/h]
LMTD	Logarithmic temperature difference [℃]
P	Power [J/s]
p_{LNG}	Average market price of LNG [$]
p_{LPG}	Average market price of LPG [$]
Q	Exchanged heat [W]
Q_{fuel}	Approximate molar flow [m^3/h]
R	Annual revenue [$]
r	Mass heat of vaporization [kJ/kg]
s	Average cost of 1 kWh [$]
T	Number of working hours per year without workovers and commissioning operations [h]
t	Temperature of the heat transfer fluid [℃]
X	Total cost of additional equipment [$]

λ	Net heating value [MJ/m^3]
η	Adiabatic efficiency