Chemical and Petroleum Engineering, Vol. 40, Nos. 7–8, 2004

CRYOGENIC ENGINEERING, PRODUCTION AND USE OF INDUSTRIAL GASES

PRODUCTION OF LIQUEFIED NATURAL GAS FOR ROAD, RAIL, AND WATER TRANSPORT APPLYING STIRLING TECHNOLOGIES

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Liquefied natural gas (LNG) is a versatile motor fuel of the 21st century. As a motor fuel for various types of transport (road, rail, air, water, etc.), it is superior in terms of energy and ecology to conventional and alternative types of motor fuel [1, 2].

LNG as a Motor Fuel in Russia: Trend of Use. Production of gaseous motor fuel (GMF) is a fast-developing trend, which will turn in the near future into a highly profitable independent branch of the gas industry. There is every ground to believe that in 7–10 years the annual volume of GMF production would reach 5–6 Bm^3, and in the longer term, 20–25 Bm^3. According to Government of Russia Resolution No. 31 of January 15, 1993, even in a free market situation the price of 1 m^3 of natural gas (NG) for various means of transportation must not be more than 50% of that of 1 liter of A-76 gasoline, which is equivalent to 1 m^3 of NG in energy content. So, at this time, natural gas is the cheapest type of motor fuel [3].

For air transport (airplanes), GMF is usable only in the LNG form, and even for other types of transport, LNG is more preferable than compressed natural gas (CNG).

The advantages of LNG as a motor fuel stem from its higher density (three times) compared to CNG, which makes it possible to significantly improve technical indices of transports, reduce size and mass of transport-borne fuel storage systems, increase payload capacity and fuel distance endurance (mileage per liter), and reduce unproductive expenditures associated with idle running through less frequent refueling (filling-in) [4].

Liquefaction reduces the gas volume almost 600 times compared to the gas volume under normal conditions, which allows the mass and volume of an NG storage system in a vehicle to be reduced 3–4 and 1.5–3 times, respectively, of what is achievable by compression of the gas. For example, for a ZIL-138A truck converted to natural gas and provided with a 300-liter cryogenic LNG storage tank, the run (mileage) with a single filling (fueling) increases 1.8-fold and the combined equipment and fuel mass decreases by 570 kg as against a vehicle running on CNG.

Use of LNG in motor vehicles is justified not only in technical and economic terms but also in ecological terms. As against conventional oil fuel, LNG reduces the content of deleterious constituents of exhaust gases, viz., carbon monoxide, nitrogen oxides, and hydrocarbons, as much as 80, 70, 45%, respectively.

It can be anticipated that in the near future LNG would become a major type of motor fuel in Russia for road transport. For instance, as estimated by VNIIGAZ (All-Russia Scientific Research Institute of Natural Gas) experts, in the Moscow region alone, the probable volume of LNG consumption in transport would rise more than 20 times and would be 25000 tons a year by 2005. By the year 2010, the LNG consumption in Russia as a whole is expected to be 2–5 million tons a year [5].

In the not-too-distant future, LNG should find use as a cheap ecologically clean fuel in domestic aviation and rocket technology. ANTK im. A. N. Tupoleva (A. N. Tupolev Scientific and Technical Aviation Group), in collaboration with the establishments of Gazprom OAO, have meanwhile conducted flight tests of a prototype TU-155 aircraft with an LNG-run

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0009-2355/04/0708-0461

TABLE 1

CGM	Type of drive	LNG output, liter/h	Power of the electric motor, kW	Mass of the machine, kg	Manufacturing company (USA)
PPG-2500	KShM	700	120	5500	Philips
Werkspoor	Rhombic	900	170	6000	Werkspoor
Model D	KShM	1100	280	7000	North American Philips
Note. The output in terms of NG is converted from the 77 K to the 111 K level.					

NK-88 engine, which has demonstrated that there is a real prospect for use of LNG for civil and cargo airplanes. Based on it, a TU-156 passenger aircraft with an NK-89 LNG engine has been developed.

Conversion of rail transport (locomotives) to LNG is of high importance. In the mid-1990s, 2TÉ116G, 2TÉ10G, and TÉM2U long-distance (main-line) and shunting (shuttle) locomotives run on LNG were developed and subjected to preliminary tests. As estimated by VNIIZhT (All-Russia Scientific Research Institute of Railroad Transportation) experts, conversion of 1000 long-distance 2200 kW locomotives to LNG may enable replacement by gas of more than 500,000 tons of diesel fuel and save about 5000 tons of diesel oil a year. The saved fuel would allow additional 700 diesel- and 2500 gas-powered locomotives to run for a year [6].

However, for wide use of LNG as a versatile motor fuel, it is essential to solve a host of specific problems relating to production, storage, and transportation of low-boiling (cryogenic) liquids under normal conditions. The most important task is to develop efficient natural gas liquefying methods that would allow building of LNG production infrastructure in Russia with due regard for the peculiarities of pipeline transporting of natural gas.

Stirling Technologies: Advanced Technologies in Production of LNG for Transport. In spite of the prospects for use of LNG as a motor fuel for various types of transport in Russia, there is still no wide network of LNG filling stations.

The LNG production infrastructure in Russia should include large liquefying complexes (mini-plants) as well as LNG filling stations small in size and output. Such an infrastructure can be built by applying Stirling technologies.

Stirling technologies for LNG production are based on application of cryogenic machines operating on Stirling cycle.

The key feature of Stirling cryogenic gas machines (CGM) is combining in a single device the processes of compression and expansion of the working medium, heat exchange between the forward and reverse streams of the working medium, and external heat exchange with the object being cooled and the surrounding medium, which allows these machines to be compact and have high thermodynamic efficiency.

In Stirling CGM, practically no internal loss occurs, and technical loss due to friction and finite temperature difference in the external and internal heat exchange processes can be eliminated or markedly reduced by sound design and selection of thermodynamic parameters. In the 100–160 K range, Stirling CGMs have an excergic efficiency of more than 50%. Gas liquefaction plants based on these machines are 2–4 times as efficient as simple throttle and expansion liquefaction cycles.

When a Stirling CGM is used, NG liquefaction (in general, the process of conversion of the gas from the equilibrium state with parameters close in temperature and pressure to the surrounding medium to the state of the liquid in equilibrium with the inherent vapor) is effected at a constant pressure through operation of the refrigerator and removal of heat from the gas being liquefied. Thus, the process is based entirely on external cooling. In this process, moisture, carbon dioxide, and other contaminants freeze on the walls of the condenser of the CGM, which makes application of costly gas-precleaning systems unnecessary. An important feature of the Stirling CGM is that it allows 100% liquefaction of the fed low-pressure gas.

At this time, several versions of single- and multi-cylinder Stirling CGM are being made in Russia and abroad. Their efficiency (capacity) allows them to be used for construction of LNG plants with outputs ranging from 50 kg/h to 10 ton/day. This range makes possible construction of small and medium stations as well as large LNG production complexes (mini-plants).

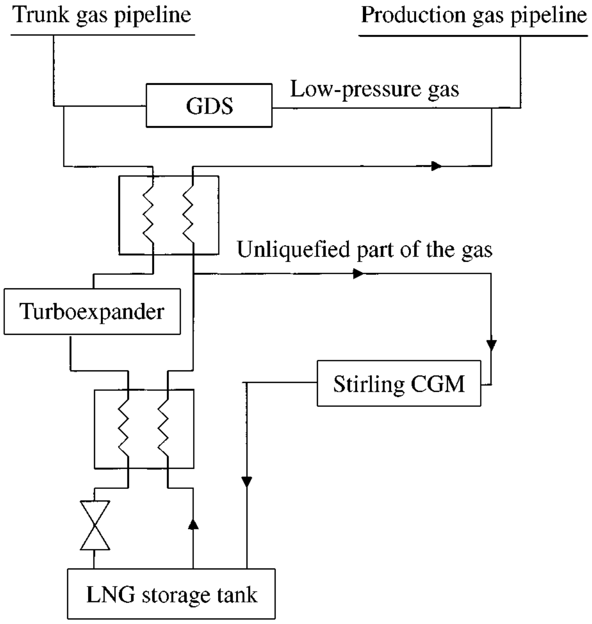

Fig. 1. Flow diagram of LNG plant.

Lately, experts from A. F. Mozhaiskii Military and Outer Space Academy and Stirling-Tekhnologii Innovation and Research Center have worked out several flow diagrams that allow, depending on the conditions and purposes of the LNG plants, most complete use of the advantages of application of Stirling technologies.

Mini-LNG Plants Based on Stirling CGM. At present, several versions of multi-cylinder Stirling CGM are being made in the world. Their efficiency (capacity) allows them to be used for construction of mini-plants for natural gas liquefaction. The technical specifications of such a Stirling CGM are cited in Table 1.

Flow diagram of an LNG plant based on a turboexpander and a Stirling CGM, which is applicable for modernizing and building gas-distributing stations (GDS), is shown in Fig. 1.

In this cycle, LNG production past the turboexpander and in the Stirling CGM occurs concurrently. Initially, the whole trunk-pipeline NG stream passes through the truboexpander, a part of it liquefies, and the unliquefied part of the low-pressure NG separates into two streams: the first one is sent for liquefaction in the Stirling CGM condenser and the second, to the production network. The effectiveness of application of Stirling CGM in this scheme depends on the fact that the low-pressure NG with a temperature close to the phase transition temperature flows into the CGM condenser, which helps significantly reduce thermodynamic irreversibility of the liquefaction processes and increase the output of the plant as a whole.

No less promising is the possibility for construction of LNG plants based on Stirling technologies at automobile gas-filling compressor stations (AGFCS) as well. This will allow significant cutting of capital expenditures through use of the infrastructure and especially of the AGFCS equipment. It is possible to build LNG plant on trunk and production pipelines with sequential arrangement of the truboexpander, intermediate expansion tank, and Stirling CGM.

In this case, the NG liquefaction process is implemented by a combined method where internal and external cooling of the natural gas is combined. The higher the pressure in the gas pipeline, the lower the energy consumption for external cooling in the Stirling CGM. The truboexpander provides for pre-expansion and cooling of the trunk-pipeline NG stream (0.5ºC at 1 atm), which helps raise the output and efficiency of the Stirling CGM through reduction of thermodynamic losses in the CGM. The cost of large LNG plants can be curtailed by inclusion of throttle valves in place of turboexpanders.

Small and Medium LNG Filling Stations Based on Stirling Technologies. The concept of small and medium LNG filling stations must take account of the specific features of NG transportation in Russia, which precisely is that there is a wide network of low-pressure (0.1–0.6 MPa) production pipelines at almost every population point. Since the capacities

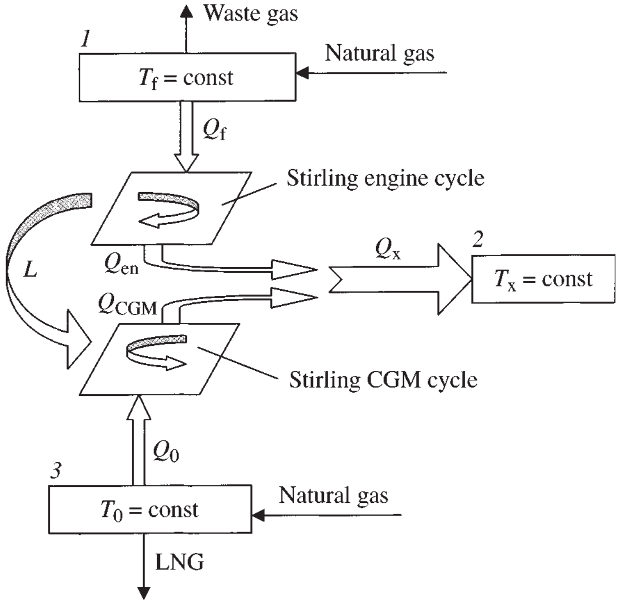

Fig. 2. Forward and reverse Stirling cycles in a Vieulemier-Tacosin machine for NG liquefaction: *1*) combustion chamber of Stirling engine; *2*) intermediate heat exchanger; *3*) heat exchanger of the Stirling CGM charge.

of such filling stations range from 100 to 1000 liter/h, for building them, only Stirling CGMs, which ensure 100% liquefaction of low-pressure gas, can be used [7, 8].

Since 2001, garage LNG filling stations based on ZIF-1000 Stirling CGM with capacities up to 20 liter/h had been built in a small lot at a domestic enterprise making use of designs offered by this author. The stations have an industrial safety contract certified by the State Committee of Standards and approved by the State Mining and Industrial Inspectorate of the Russian Federation for application (Construction and Application License No. RRS-56-000104).

Technical and economic appraisal by independent experts has revealed that LNG production based on Stirling CGM is highly profitable. For instance, the price of 1 liter of LNG produced in modular NG liquefaction plants based on Stirling technologies is not higher than two rubles. In this context, the payback time for garage stations themselves that are based on Stirling CGM is not more than 2.5 yr [9].

LNG Filling Stations Based on Vieulemier-Tacosin Machines (Stirling–Stirling cycle). In situations where electric power is in short supply and there is a low-pressure gas supply line, for constructing LNG filling stations it is promising to employ Vieulemier-Tacosin heat-utilizing cryogenic gas machines (HCGM) that operate on combined Stirling–Stirling cycle. The distinctive feature of this type of machines consists in combining a cryogenic machine and a heat engine in a single apparatus, which is designed for operation of the machine without interim conversion of the heat energy into other forms of energy. The cycle is executed by supplying heat from an external source, for which heat of combustion of the NG is used. Practical experience has shown that the Vieulemier-Tacosin machine is capable of functioning efficiently at temperatures up to 15 K.

In Fig. 2 is shown conjugation of forward and reverse Stirling cycles in a Vieulemier-Tacosin machine for NG liquefaction, where T_f is the fuel combustion temperature, Q_f is the heat of combustion of the fuel fed into the engine, Q_{en} is the quantity of heat released from the engine to the surrounding medium, Q_{CGM} is the quantity of heat released from the CGM to the surrounding medium, T_0 is the refrigeration temperature, and Q_x is the quantity of heat released from the Vieulemier-Tacosin HCGM to the surrounding medium.

Experts of Stirling Tekhnologii IITs have developed several NG liquefaction schemes involving use of Vieulemier-Tacosin machines. A line diagram of a self-contained LNG plant based on air-cooled HCGM (Russian Federation Patent

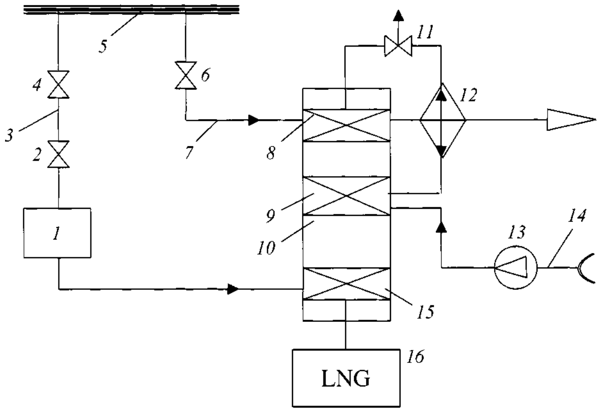

Fig. 3. Line diagram of self-contained LNG plant.

No. 2159400) is shown in Fig. 3. This plant consists of a Vieulemier-Tacosin machine *10*, which includes a combustion chamber *8*, an intercooler *9*, and a charge heat exchanger (cooler) *15*. The flow and order of distribution of the working medium inside the machine are maintained by reciprocating motion of the piston group of the engine and the refrigerating machine, which together form the Vieulemier-Tacosin HCGM.

The self-contained LNG plant operates as follows. Air from the surroundings is fed by a compressor *13* through the main line *14* into the combustion chamber *8* of the Vieulemier-Tacosin HCGM. The air initially passes through the intermediate heat exchanger *9* and warms up in the heat exchanger *12*. Natural gas from the gas pipeline *5* is also fed into the combustion chamber *8* via the main line *7* through the control valve *6*. The heat generated on account of combustion is transferred to the working medium of the engine of the Vieulemier-Tacosin machine, as a result of which, upon use of the reciprocating motion of the piston group, cryogenic-level cold is generated in the charge heat exchanger *15*.

The exhaust gases from the combustion chamber *8* pass into the heat exchanger *12*, where they warm up the air fed into the combustion chamber and then are let off into the atmosphere. The air fed by the compressor passes through the intermediate heat exchanger *9*, cools the HCGM, warms up in the heat exchanger *12*, and enters the combustion chamber in the required amount through the distribution valve *11*. The natural gas from the gas pipeline *5* passes via the liquefaction line *3* through the control valve *4* into the throttle valve *2*, and then, having expanded, undergoes precooling, collects in the expansion tank *1*, and enters the charge heat exchanger *15*, where it liquefies on account of heat exchange with the working medium of the Vieulemier-Tacosin HCGM. Thereafter, the LNG is discharged into a heat-insulated tank *16* designed to store the liquefied gas.

Thus, the infrastructure for production of LNG for any type of transport can be built in the shortest time by employing Stirling technologies for natural gas liquefaction. In this context, as operation of pilot plants based on Stirling CGM has shown, the cost of the LNG produced is 2.5 times lower than that of conventionally used oil products.

REFERENCES

1. N. G. Kirillov, "Liquefied natural gas – a versatile energy carrier of the 21st century," *Industr.*, No. 3 (29), 113–18 (2002).
2. N. G. Kirillov, "Liquefied natural gas: social, ecological, and energy aspects of use in transportation," *Industr.*, No. 4 (26), 59–63 (2001).
3. A. D. Sedykh and V. M. Rodnyavskii, "Gasprom's policy on using natural gas as an engine fuel," *Gaz. Promyshl.*, No. 10, 8–9 (1999).
4. "Natural gas as a motor fuel: LNG or CNG?" *Avtomob. Transport*, No. 5, 44–45 (2002).

5. B. G. Bergo and E. V. Karpov, “Liquefied natural gas production technology,” *Potentsial*, No. 1, 60–63 (2001).
6. G. A. Fofanov and Yu. P. Korobov, “Fuel for locomotives – natural gas,” *Zheleznodorozhn. Transp.*, No. 14, 70–72 (1998).
7. N. G. Kirillov, “Producing liquefied natural gas for vehicles,” *Khim. Neftegaz. Mashinostr.*, No. 6, 17–19 (2001).
8. N. G. Kirillov, “Building infrastructure for production of LNG for motor vehicles in Russian Federation,” *Neftegaz. Tekhnol.*, No. 3, 21–24 (2001).
9. N. G. Kirillov, “Individual and garage LNG filling stations,” *Gaz. Promyshl.*, No. 9, 55–57 (2001).