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I. Kudryavtsev, *PhD, Associate Professor, Associate Professor of the Department*
(ORCID 0000-0001-6677-9289)
V. N. Karazin Kharkiv National University, Kharkiv, Ukraine

DEVELOPMENT OF ENVIRONMENTALLY SAFE CRYOGENIC POWER INSTALLATIONS FOR VEHICLES

Global concerns about environmental pollution due to car emissions, as well as global warming due to an increase in the amount of greenhouse gases, including carbon dioxide, in the Earth's atmosphere have led to active searches for alternative fuels for transport. Although the most well-known of the proposed alternative solutions is hydrogen, there are a number of practical and economic problems in its applying that may limit its widespread use. This paper shows that cryogenic liquids, primarily nitrogen, derived from the atmosphere, can be effective and relatively inexpensive clean energy carriers for cars. A comparative analysis of the energy characteristics of power plants of various types has been accomplished. The concept of an environmentally safe cryogenic power plant on liquid nitrogen is proposed, the main advantages of using nitrogen as an energy carrier are analyzed. A mathematical model based on a modified perturbation theory and a computer program in the shell MATLAB-SIMULINK for calculating the basic physical characteristics of molecular nitrogen in a wide range of pressures and temperatures have been developed. The possibility of implementing an environmentally clean closed-loop production of electricity based on renewable energy sources and its utilization to produce liquid nitrogen from atmospheric air with subsequent use in cryogenic transport is considered. The principle of operation of a cryogenic power plant on liquid nitrogen, including a cryogenic gasification tank, an air heat exchanger and a pneumatic engine, is described in detail. Numerous theoretical and experimental studies of relevant pneumatic engines have been carried out. The main results of the development and experimental testing of cryogenic vehicles in the USA and Ukraine are presented.

Keywords: environmental safety, automobile transport, cryogenic power plant, liquid nitrogen, renewable energy sources, pneumatic engine

1. Introduction

The finite quantity of hydrocarbon fuels that are available, the increasing cost of such fuels, the harmful pollutants and greenhouse effect produced by combustion of such fuels in the automotive internal combustion engines (ICE), and as a result the decreasing of oxygen content, global warming and negative environmental impact together indicate that it is necessary to develop alternatives to the transport power sources in current widespread use and especially in regions with high density of population, where the ecological aspect is the most essential for the human health and sustainable development. Electric vehicles (EV) concepts have their own disadvantages. EVs based on chemical batteries are not almost non-polluting and need their regular replacement, and ones based on hydrogen technologies are very expensive and usually use fossil natural gas to produce hydrogen.

One alternative that has been investigated to solve these problems and increase the global energy efficiency is the use of cryogenic power systems, a concept in which a cryogenic substance is used as a working fluid and free heat energy is taken from the environment, specifying the working cycle somewhat opposite to internal combustion engines. Examples of such power systems include those that utilize liquid nitrogen (LN2) to propel the vehicles that were designed and built in the USA at the University of North Texas (UNT), the University of Washington and in the Ukraine at the Kharkov Universities and Research Institutes [1-8]. In the power systems of these vehicles liquid nitrogen, produced by external electricity source, is stored at the cryogenic tank, then vaporized, heated at the heat exchanger and expanded through the pneumatic engine to produce work. Another kind of analogous power system contain high-pressure vessel with compressed air, heat exchanger and pneumatic engine. No burning processes take place during the operation of such a power system. Moreover, gaseous nitrogen after working cycle returns to the atmosphere, do not changing the environmental sustainability (Fig. 1). The numerical estimations indicate that along with environmentally friendly operation such automotive power systems have the specific energy output on the same level as electric vehicles, but have no problem with the short living time and harmful utilization of chemical batteries. Moreover, the economical estimation made in the present paper shows the certain advantages of cryogenically powered vehicles against traditional ones, burning hydrocarbon fuels.

From the complex point of view it is necessary to combine the transportation problems with the energy production problems, while they have the similar impact to the environment and sustainable development. That means the need of development of alternative and renewable energy sources, such as solar, wind and hydro power stations. That’s why at present USA, CNR and other industrial countries have established a national goal on the increased utilization and penetration of solar and wind energy systems. One of the main problems for such systems is the need for local energy storage and utilization, which has the present solution by using heavy, expensive and short-living chemical batteries. It can be solved more effectively in producing compressed air or liquid nitrogen with their further utilization in automotive cryogenic power systems (see Fig. 1).

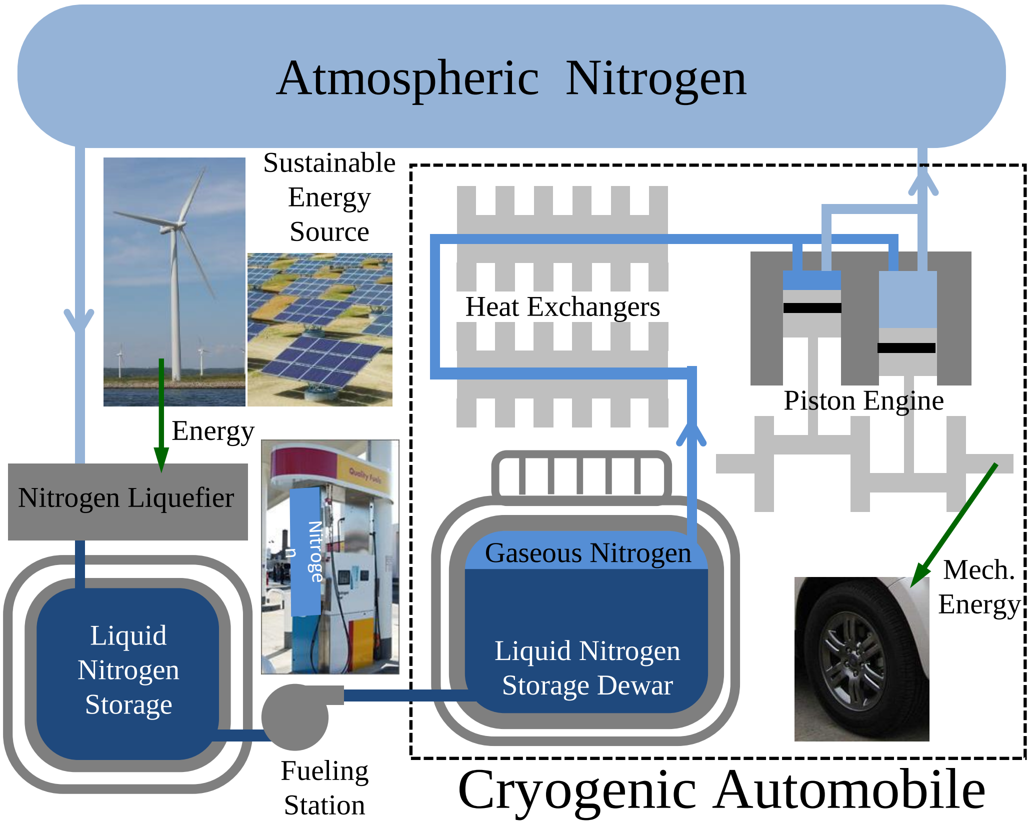

Fig. 1. A general concept of LN2 production and utilization in clean vehicles

Besides, the manufacturing of LN2 by electricity, obtained from renewable power sources can be incorporated with the rural needs for food conservation and quality transportation under the conditions of low temperatures. Some of such systems as cryogenic refrigerated trucks based on GAZ-53A trucks were developed in Kharkov Institute for Low Temperature Physics and Engineering in 80th and more than 600 cryo-trucks were used in the industry of former Soviet Union. Such a project “ECOFRIDGE” was recently renewed and received the financial backing from European Bank for Reconstruction and Development (EBRD) through the innovative Sustainable Energy Initiative.

2. The principle of operation of the liquid nitrogen powered automobile. Analysis of the literature and problem statement

The underlying principle of a liquid-nitrogen-powered vehicle is to move freely available heat from the environmental atmosphere (nominally at 300 K) through a heat engine down a temperature gradient to a heat sink at liquid nitrogen temperature (nominally 77 K). The first and most obvious developments focused on converting liquid cryogenic fluid stored onboard a vehicle into high-pressure gas at atmospheric temperature for injection into mechanical work extraction devices (i.e., turbines or pistons) that provide propulsion are presented in [1-4]. This path is similar to the development of early injection steam engines in the 1800's. The main advantages of this approach are 1) its relative ease of construction or conversion from existing vehicles with ICE; 2) working temperatures of pneumatic engines are close to ambient, and working cycle is close to isothermal with small energy loses; 3) environment is free and unrestricted heat energy source.

The general scheme of cryogenic vehicle operation is presented in fig. 2. The potential for superior cryogenic vehicle energy conversion efficiency compared to conventional automobiles motivates development of thermodynamic cycles that capitalize on this concept. The bounding efficiency approximation of such an arrangement, the Carnot efficiency for heat engines, is over 74.3 %. This result compares favorably to the ideal Otto cycle efficiency, which exceeds 74.3 % only at compression ratios above 30:1. Due to engine knock, typical automobile compression ratios cannot exceed 12:1, with ideal Otto efficiency of 63% [9].

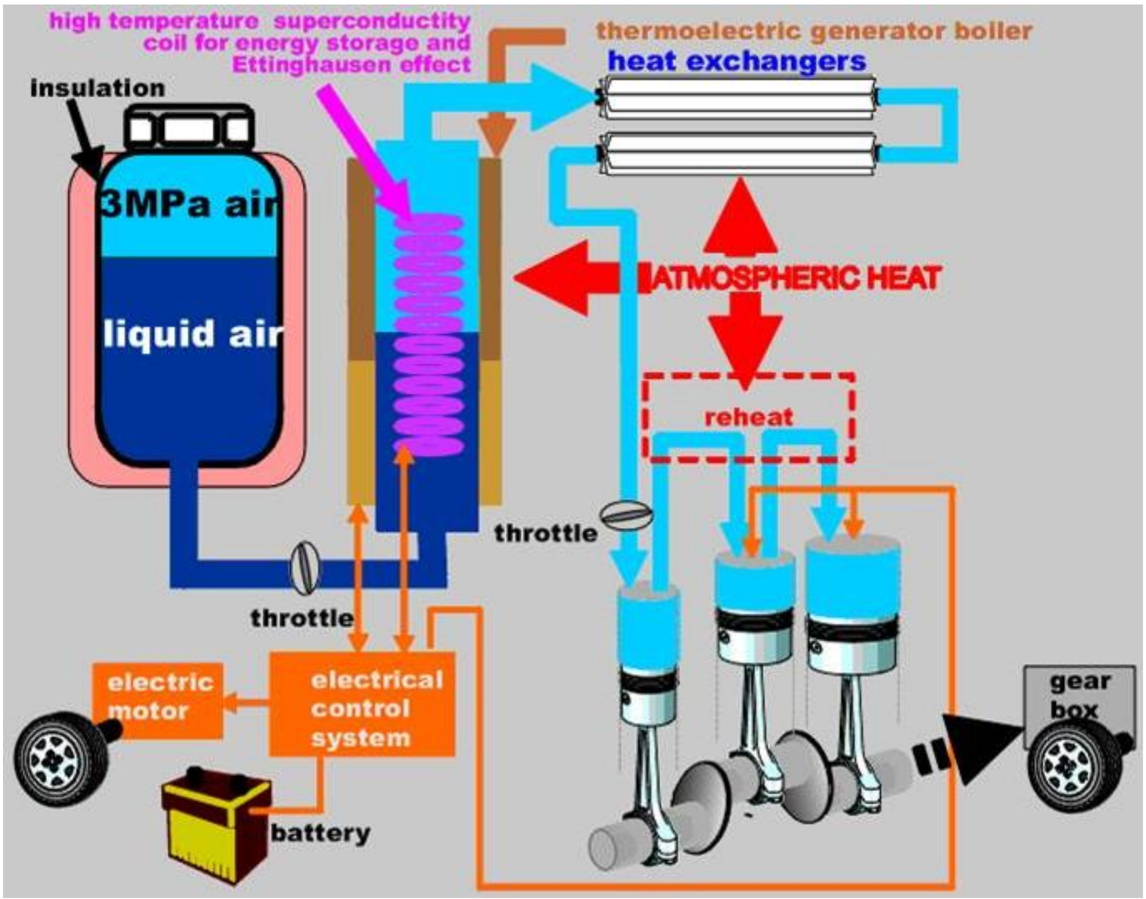

Fig. 2. Schematic of cryogenic automotive power system operation

The first LN2 powered vehicles were presented and successfully tested simultaneously in the University of North Texas, University of Washington in USA and Kharkov Universities and Research Institutes in Ukraine [2, 5, 8]. Fig. 3 shows the corresponding cryogenic cars developed in UNT (a) and Kharkov (b) at 1997-2004.

Fig. 3. Liquid nitrogen powered prototype vehicles, built by a) UNT (left), b) Kharkov research team (right)

3. The technical attraction and transport application of cryogenic fuels. Purpose and tasks of the research

Among the most attractive features of cryogenic vehicles is that they are absolutely pollution free. The fuel is extracted from the atmosphere when it is created, and the vehicle effluent is returned to the atmosphere chemically unaltered from its original state. Unlike other potential alternative fuel sources, the technology of producing and distributing cryogenic liquids is well known, and minimal to zero development work is required in this area.

Another attractive feature of cryogenic liquid for vehicle propulsion is its relatively high specific energy and energy density in comparison to electric batteries. The maximum available specific energy (ability to perform useful work) of LN2 is 770 kJ/kg [1,5,7]. Importantly since energy can be extracted from working fluid until its temperature matches the ambient environment, the energy of cryogenic fuel increases the warmer the ambient temperature becomes. On hot days when conventional vehicles overheat, cryogenic vehicles become more efficient and their fuel supply energy increases. Table 1 compares the specific energy of several cryogenic fuels undergoing a variety of thermodynamic processes as versus batteries.

Tab. 1. Comparison of energy content for different power systems [9]

Energy Carrier	Specific Energy (kJ/kg)
Lead Acid Batteries	190
N2 3.5 MPa – adiabatic	320
N2 3.5 MPa – one reheat	400
N2 3.5 MPa – two reheats	415
N2 3.5 MPa – isothermal	425
He Brayton cycle with N2 Sink	435
Ethane-Methane – Rankine cycle	460
Gasoline	44000

Gasoline's enormous specific energy compared to other energy carriers arises because its consumption in conventional vehicles requires combustion, the release of stored chemical energy through a reaction that transforms high-energy molecules to low-energy molecules. By contrast cryogenic fluids store energy as latent and sensible heat, undergoing no chemical changes when consumed. The consequence of this phenomenon is lower specific energy than chemical energy storage fuels. However, lack of chemical changes in the working fluid during consumption yields pollution-free operation, which is not the case for gasoline-fired engines. Two conclusions are clear from table 1. First, any nonchemical-storage gasoline alternative must weigh approximately 100 to 250 times the mass of gasoline required to achieve the same mileage. Second independent which gasoline alterative is used, consumption of available energy from these carriers must occur with every consideration toward maximum efficiency. For cryogenic vehicles, the first conclusion is addressed by increasing fuel capacity using the whole structure of the vehicle, a practice already applied to increase range of passenger jets by storing fuel in the wings. The second conclusion is a fertile area of on-going research.

The additional advantages of using liquid nitrogen as a working fluid for cryogenic automotive power systems compared to gasoline and hydrogen are as follows:

1) Molecular N_2 is a chemically inert, nonflammable, and safe gas that is a normal component of air. Cryogenic LN2 power systems can be used around ignition sources, in airports, inside buildings, and near flammable materials with no risk of combustion. In this respect, it is far safer than gasoline or hydrogen.

2) Nitrogen is freely available in Earth's atmosphere. Unlike fossil fuels, Nitrogen gas is not isolated in particular geographic or political regions, meaning it is equally available and accessible to all countries in the world. Any source of energy can be harnessed to liquefy nitrogen, and it can be produced anywhere on the Earth's surface. If produced using a renewable energy source like wind or solar LN2 is a completely renewable, environmentally benign energy carrier.

3) The thermodynamic properties of nitrogen are well studied for a wide range of temperatures range, and its production is extremely well-developed in industrialized countries. The price for 1 liter of LN2 in USA is $0.06/liter ($0.227/gal) and at 10-20 times lower than the corresponding price of gasoline [1,6]. In addition, the production cost of liquid nitrogen in a hundred times lower than the cost of liquid hydrogen.

4) Liquid nitrogen can be stored at a pressure close to atmospheric and does not require containment in a heavy pressure vessel.

5) Pneumatic engines operate on heated gaseous nitrogen at temperatures close to ambient temperature without combustion. No greenhouse gasses or harmful pollutants are created during consumption of LN2 for transportation. The spent gaseous nitrogen returns to the atmosphere without disturbing the ecological balance of the environment.

Availability of LN2 onboard a vehicle creates new synergistic opportunities to integrate novel energy saving technologies based on high-temperature superconductors: superconducting electric motors, generators, magnetic bearings, flywheel, and inductive energy storage (SMES). In particular, compact superconducting asynchronous motors outputting up to 40 kW of power have been already been developed. These motors have masses 3-5 times smaller than conventional electric motors with the same power output. A hybrid cryogenic-electric vehicle could produce energy in an optimized cryogenic power system that feeds superconducting motors attached to each wheel. The conventional automobile arrangement, using a single large motor with complex transmission to distribute power to the wheels, could be supplanted. Lighter superconducting motors would enable each wheel to have an independent motor, leading to substantial simplification in vehicle construction, improved energy management, and increase in efficiency. Moreover, due to the sufficient progress in solar power generation systems with efficiency up to 40 % the hybrid cryogenic-electric vehicles can be developed by combining the different alternative and environmentally friendly energy sources.

4. Technical progress and implementability. Results of research

The research presented in this paper is provided by international collaborative partnership by the University of North Texas, USA and Ukrainian National Institutions.

The Ukrainian research team includes leading specialists from the V.N.Karazin

Kharkov National University, Kharkov National Automobile and Highway University, Kharkov Institute for Low Temperature Physics and Engineering, Kharkov Institute for Problems in Machinery and National Science Center Kharkov Institute of Physics and Technology, Academy of Sciences of Ukraine.

Different models of pneumatic engines, heat exchangers, cryogenic pumps and evaporators, pneumatic and cryogenic automotive power systems, electronic control systems and cryogenic vehicles, operating on compressed air / liquid nitrogen have been developed and successfully tested. The mathematical models and computational codes for modeling the operation of the piston pneumatic engines, air heat exchangers, cryogenic pumps and for calculation a complete set of parameters of all technical gases, for various physical conditions, have been developed as well. Ukrainian research group has published near 60 scientific papers on these investigations and obtained 9 Patents and Copyrights. Let us consider these results in more detail.

The statistical mechanical methods of a perturbation theory were used for the description of liquid and gaseous states of the molecular nitrogen. Advantages of the proposed calculation method for thermodynamic characteristics are the minimum number of the initial data necessary for calculations, and absence of fitting parameters or empirical correlations. The numerical calculations accomplished for pressure of saturated vapor, heat capacity and sound velocity of the molecular nitrogen agree well with the available experimental data [10]. Theoretical approach developed allows calculate with high precision the real gas properties of cryocooled nitrogen, used in the cryogenic vehicle in wide temperature and pressure regions, even where the experimental data is absent for today.

A computer code for calculation of the thermodynamic characteristics (density, heat capacity, internal energy, entropy, enthalpy, sound velocity, etc) of liquid and gaseous nitrogen on the basis of modified perturbation theory in wide temperature (70-1000 K) and pressure (0.1-50 MPa) regions has been developed in MATLAB-SIMULINK software. Testing shows that it gives reasonable agreement with the available experimental data. The program allows calculate the complete set of thermodynamic functions of real nitrogen in wide ranges of temperatures and pressures, which is rather actual for modeling of the pneumatic engine operation at the high pressures and correct design of the cryogenic equipments at low temperatures. The results of calculations are presented in three-dimensional format, convenient for the theoretical analysis and applications (see fig. 4).

In order to accomplish the computer simulation of the pneumatic cylinder operation the mathematical model of the pneumatic cylinder with a bilateral drive for the cryogenic power system was developed. It is based on the differential equations, describing gas and piston dynamics [11]. The purpose of developed mathematical model is the determination of the basic dynamic parameters, namely: pressure of gas in working cylinders, position and speed of the piston in time, frequency of work and calculation on their basis the operational characteristics of the considered pneumatic engine. The corresponding computer program in MATLAB-SIMULINK software for simulation of the operation of the pneumatic cylinder was developed and tested. As a result of computer modeling the dynamic characteristics (pressure, velocity, specific work, power, efficiency) of working process as well as PV diagram were calculated for the given pneumatic cylinder and shown the whole consistency with the measured experimental data. The analysis of consecutive stages of work of the pneumatic cylinder was made. Using of such a program the optimization of the piston pneumatic engine was accomplished that can lead to development more efficient cryogenic vehicle. It was shown that the efficiency of the pneumatic engine considered can reach the value 60 %.

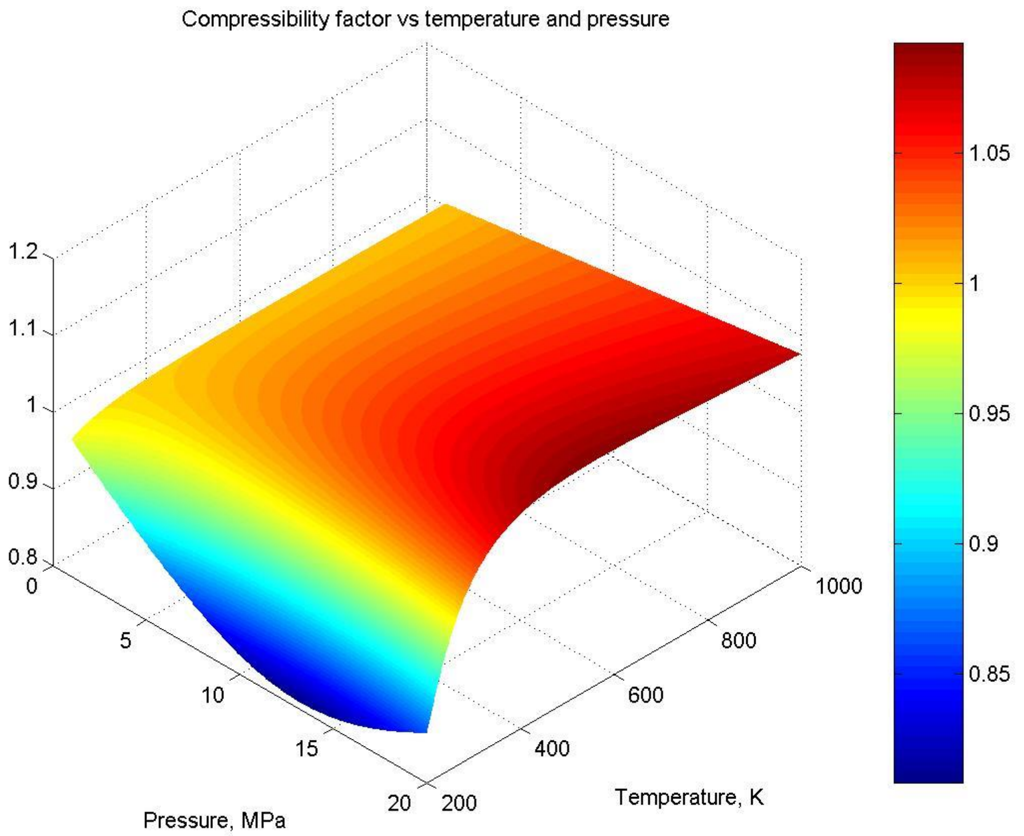

Fig. 4. Compressibility factor in various temperature and pressure regions for the nitrogen

In order to compare the results of modeling with the experimental data and investigate the control systems for the different pneumatic engines the corresponding experimental stand with the data acquisition system was developed (see fig. 5). As a result of research accomplished three different pneumatic engines were developed and tested The computer control system for two double acting pneumatic cylinders was developed, which correspond to four-cylinders pneumatic engine.

Fig. 5. Experimental stand for pneumatic engines development

In order to improve general efficiency of the cryogenic vehicle, the prospects of development and kinds of application of electric motors and generators, magnetic bearings and suspensions, as well as inductive energy storage, on the basis of high temperature superconductors for automobile transport have been studied as well.

In 2000-2003 years Ukrainian research group has accomplished the computer modeling, design and development of the basic units for the first automotive cryogenic power system: experimental pneumatic engine with the power up to 1 kW, heat exchanger and evaporator of liquid nitrogen, which were successfully tested.

In October, 2004 this research team successfully assembled and tested first in the Ukraine and Europe experimental model of cryogenic vehicle operated on compressed air and then on liquid nitrogen (see fig. 3b) [8]. The technical characteristics of such a vehicle are presented in table 2. It was modified and equipped with additional heat exchangers in April, 2005. This research was done due to the CRDF grant "Development of optimum liquid nitrogen gasification process for the cryogenic vehicle" № UE2-2448-KH-02, which was received together with UNT and successfully accomplished in 2002–2004.

Tab. 2. Technical characteristics of first Ukrainian cryogenic vehicle (Fig. 3 b)

Parameters of vehicle	Parameters of cryogenic tank-evaporator	Engine characteristics
Mass of vehicle is 280 kg. Gas consumption is 10 g/s. Maximum speed is 10 km/h. Maximum frequency of the engine's shaft at the working pressure 8 atm is 2000 rot/min.	Height is 900 mm. Diameter is 500 mm. Mass is 30 kg. Capacity is 30 L of liquid nitrogen. Gas supply 5-10 g/s. Output temperature of gaseous nitrogen is 173 K (-100 °C).	Two-cylindrical engine. Diameter of cylinder is 40 mm. Piston stroke is 45 mm. Volume of cylinders is 113 cm^3. Power is 0.7-0.8 kW (1 hp) at 900-1800 rot/min. Dimensions 200x200x150 mm^3. Mass is 33 kg.

Technical parameters of the UNT cryogenic vehicle, which was successfully tested in USA, presented at table 3.

Tab. 3. Operational parameters for first UNT cryogenic vehicle (Fig. 3a)

Parameters of vehicle	Parameters of cryogenic tank-evaporator	Engine characteristics
Suspension from Volkswagen, total mass with the full tank is 700 kg (tank capacity is 180 L). Maximum speed is 40 km/h. Range of running on full tank is 24 km at a speed 32 km/h.	Nitrogen pressure in evaporator reaches the value 1,2 MPa (approx. 12 atm), then it is reduced up to 0,7 MPa before entering the pneumatic engine.	Pneumatic engine of Vankel type with a power 9 hp. Pneumatic engine, having small sizes, possesses sufficient torque and acceleration 1,1 m/s^2 on small velocities.

5. Conclusions

Thus the development of cryogenically powered vehicles has direct application to global problems resulting from the continued use of carbon and hydrocarbon fuels. It provides a new range of manufactured products in industry and agriculture and will help to accomplish more sustainable development, increase the energy efficiency and reduce sufficiently the harmful pollution, especially in regions with high density of population.

References

1. Knowlen, C., Williams, J., Mattick, A. T., Deparis, H., Hertzberg, A. (1997). Quasi-isothermal expansion engines for liquid nitrogen automotive propulsion. In Proc. of the SAE Future Transp. Techn. Conf. San Diego, CA, USA, SAE Technical Paper Series 972649.

2. Williams, J., Knowlen, C., Mattick, A.T., Hertzberg, A. (1997). Frost-free cryogenic heat exchanger for automotive propulsion. In Proc. of 33-rd AIAA/ASEE Joint Propulsion Conference & Exhibition. Seattle, USA.

3. Bondarenko, S. I., Fenchenko, V. N. (1997). Propulsion installation for the vehicle. Patent of Ukraine N 22721A.

4. Knowlen, C., Mattick, A. T., Bruckner, A. P., Hertzberg, A. (1998). High efficiency energy conversion systems for liquid nitrogen automobiles. Society of Automotive Engineers, Paper 981898, 1–7.

5. Plummer, M. C., Koehler, C. P., Flanders, D. R., Reidy, R. F., Ordonez, C. A. (1998). Cryogenic heat engine experiment. Advances in Cryogenic Engineering, 43, 1245-1252.

6. Plummer, M. C., Reidy, R. F. (1999). Feasibility of liquid nitrogen powered vehicles. A presentation to the American Chemical Society, 218th National Meeting. New Orleans, Louisiana, USA.

7. Turenko, A. N., Pyatak, A. I., Kudryavtsev, I. N., Timchenko, I. I., Jadan, P. V., Bondarenko, S. I., Levin, A. Ya., Samarskii, V. A. (2000). Non-polluting cryogenic transport: modern state of problem. Bulletin of the Kharkov National Automobile and Highway University (Ukr), 12–13, 42–47.

8. Turenko, A. N., Bogomolov, V. A., Bondarenko, S. I., Kudryavtsev, I. N., Pyatak, A. I., Klimenko, V. I., Levin, A. Ya., Levchenko, N. M., Murinets-Markevich, B. N., Kramskoy, A. V., Archipov, A. V., Lukashev, I. V., Kanishev, I. N., Klunniy, A. (2005). Development first in the Ukraine demonstrational model of non-polluting automobile with cryogenic power plant. International Scientific Journal for Alternative Energy and Ecology, 4(24), 93-98.

9. Ordonez, C. (2000). Liquid nitrogen fueled, closed Brayton cycle cryogenic heat engine. Energy Conversion and Management, 41, 331–341.

10. Cho, H. M., Kudryavtsev, I. N., Kramskoy, A. V. (2014). Methodology for describing different phase states of molecular nitrogen. Journal of Energy Engineering, 23(4), 215–222.

11. Kudryavtsev, I. N., Kramskoy, A. V., Pyatak, A. I., Plummer, M. C. (2005). Computer simulation of pneumatic engine operation. International Scientific Journal for Alternative Energy and Ecology, 3(23), 80–89.

І. М. Кудрявцев, *к.т.н., доцент, доц. каф.*
Харківський національний університет імені В. Н. Каразіна

РОЗРОБКА ЕКОЛОГІЧНО БЕЗПЕЧНИХ КРІОГЕННИХ СИЛОВИХ УСТАНОВОК ДЛЯ ТРАНСПОРТНИХ ЗАСОБІВ

Світова стурбованість у зв'язку із забрудненням навколишнього середовища через автомобільні вихлопи, а також глобальним потеплінням, внаслідок збільшення кількості парникових газів, в тому числі вуглекислого газу, в атмосфері Землі викликала активні пошуки альтернативних видів палива для використання на транспорті. Хоча найбільш відомим з пропонованих альтернативних рішень є водень, в його використанні існує ряд практичних і економічних проблем, які можуть обмежити його масове застосування. У даній роботі показано, що кріогенні рідини, в першу чергу азот, отриманий з атмосфери, можуть бути ефективними і відносно недорогими екологічно чистими енергоносіями для автомобілів. Виконано порівняльний аналіз енергетичних характеристик силових установок різного типу. Запропоновано концепцію екологічно безпечної кріогенної силової установки на рідкому азоті, проаналізовано основні переваги застосування азоту в якості енергоносія. Розроблено математичну модель на основі модифікованої теорії збурень та комп'ютерну програму в оболонці MATLAB-SIMULINK для розрахунку основних фізичних характеристик молекулярного азоту в широкому діапазоні тисків і температур. Розглянуто можливість реалізації екологічно чистого замкнутого циклу виробництва електроенергії на основі відновлюваних джерел енергії та її утилізації для отримання рідкого азоту з атмосферного повітря з подальшим застосуванням на кріогенному транспорті. Детально описаний принцип роботи кріогенної силової установки на рідкому азоті, що включає кріогенний бак-газифікатор, повітряний теплообмінник і пневматичний двигун. Виконано численні теоретичні та експериментальні дослідження відповідних пневматичних двигунів. Представлені основні результати розробок і експериментальних випробувань кріогенних транспортних засобів в США та на Україні.

Ключові слова: екологічна безпека, автомобільний транспорт, кріогенна силова установка, рідкий азот, поновлювані джерела енергії, пневматичний двигун

Література

1. Knowlen C., Williams J., Mattick A. T., Deparis H., Hertzberg A. Quasi-Isothermal Expansion Engines for Liquid Nitrogen Automotive Propulsion // In Proc. of the SAE Future Transp. Techn. Conf. San Diego, CA, Aug. 6–8, 1997. SAE Technical Paper Series 972649.

2. Williams J., Knowlen C., Mattick A. T. and Hertzberg A. Frost-free cryogenic heat exchanger for automotive propulsion // In Proc. of 33-rd AIAA/ASEE Joint Propulsion Conference & Exhibition. Seattle, USA. 1997.

3. Propulsion installation for the vehicle. Bondarenko S.I., Fenchenko V.N.: Patent of Ukraine N 22721A, 1997.

4. Knowlen C., Mattick A.T., Bruckner A.P., Hertzberg A. High Efficiency Energy Conversion Systems for Liquid Nitrogen Automobiles // Society of Automotive Engineers, Paper 981898. 1998. P. 1–7.

5. Plummer M. C., Koehler C. P., Flanders D. R., Reidy R. F., Ordonez C. A. Cryogenic Heat Engine Experiment // Advances in Cryogenic Engineering. 1998. Vol. 43. P. 1245–1252.

6. Plummer M. C., Reidy R. F. Feasibility of Liquid Nitrogen Powered Vehicles // A presentation to the American Chemical Society, 218th National Meeting. New Orleans, Louisiana. 1999.

7. Turenko A. N., Pyatak A. I., Kudryavtsev I. N., Timchenko I. I., Jadan P. V., Bondarenko S. I., Levin A. Ya., Samarskii V. A. Non-polluting cryogenic transport: modern state of problem // Bulletin of the Kharkov National Automobile and Highway University (Ukr). 2000. Vol. 12–13. P. 42–47.

8. Turenko A. N., Bogomolov V. A., Bondarenko S. I., Kudryavtsev I. N., Pyatak A. I., Klimenko V. I., Levin A. Ya., Levchenko N. M., Murinets-Markevich B. N., Kramskoy A. V., Archipov A. V., Lukashev I. V., Kanishev I. N., Klunniy A. Development first in the Ukraine demonstrational model of non-polluting automobile with cryogenic power plant // International Scientific Journal for Alternative Energy and Ecology. 2005. № 4 (24). P. 93–98.

9. Ordonez C. Liquid Nitrogen Fueled, closed Brayton cycle cryogenic heat engine // Energy Conversion and Management, 2000. V. 41, P. 331–341.

10. Cho H. M., Kudryavtsev I. N., Kramskoy A. V. Methodology for Describing Different Phase States of Molecular Nitrogen // Journal of Energy Engineering. 2014. Vol. 23. № 4. P. 215–222.

11. Kudryavtsev I. N., Kramskoy A. V., Pyatak A. I., Plummer M. C. Computer simulation of pneumatic engine operation // International Scientific Journal for Alternative Energy and Ecology. 2005. № 3 (23). P. 80–89.

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