The Large Scale Development Concept with Regard to Innovative Systems of Production and Distribution of Methane-Hydrogen Fuel as an Effective Alternative Energy Source

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Introduction

Qualitative change in the environmental requirements imposed by laws of developed countries in energy and transportation sectors is an important factor of the inevitable transition to the mass use of new energy technologies. In the course of the transition to new environmental standards, the economic life and markets of developed countries can gradually become inaccessible to countries or individual companies that fail to comply with the established requirements. In essence, this refers to technological and financial and economic foundations of a new economic structure to be built by a group of developed countries within the period of up to 2025-2030. This economic structure will permit to cover the world community needs for high-quality fuel and energy resources, with the maximum possible limitation of the environmental damage.

The basic principles of the new economic structure include as follows:

- diversification of external energy supply sources of developed countries, ensuring their stability and high sustainability, in particular, involving national and collective security procedures;
- relocating of environmentally harmful and energy intensive enterprises to the controlled "third world" countries;
- the use of highly efficient and environmentally friendly energy technologies; creation of a cutting-edge technology base in the energy industry;
- expanded use of renewable energy sources.

The increasing natural gas importance for regional and global energy industries necessitates the creation of technologies improving efficiency and expanding the use of natural gas.

One of the key technologies based on innovative solutions in the gas industry consists in the use of innovative hydrogen-bearing energy carriers produced from natural gas. Such carriers can provide efficient ways of saving natural gas on the basis of well-proven industrial technologies, processes and catalysts. It implies effective production of methane-hydrogen mixtures (MHMs), with the hydrogen content ranging from 20% to 44-48%.

Methane-Hydrogen Fuel Technology Concept

The 2011 International Energy Agency study illustrated that by 2035 the natural gas output will have exceeded 4,000,000,000 tonnes of oil equivalent (TOE) to become almost equal to the contribution of oil to the world's energy supply. Annual natural gas demand increases by 2% with the total energy consumption growth of 1.2%.

Over the longer term, hydrogen fuel is to replace natural gas. Hydrogen is the most efficient and environmentally friendly fuel (Table 1). World's hydrogen output exceeds 550,000,000,000 m^3. Its lower heating value per mass unit is 2.75 times as much as that of gasoline; it also has a greater lower flammable limit and a considerably wider fuel-air mixture ignition range (from 4% to 75% by volume), an order of magnitude greater laminar flame propagation speed (about 3 m/s), lower energy needed to ignite a stoichiometric mixture (0.018 mJ), shorter quenching distance (0.6 mm) and higher temperatures of combustion (2300 K for laminar hydrogen/air flames) and auto-ignition in fuel-air mixtures (850 K). The above unique hydrogen properties provide for a 1.5-1.7 times higher efficiency of heat engines, with the actual cycle of a hydrogen-running engine being significantly closer to the theoretical one than the actual cycle of an engine run on any hydrocarbon fuel. Transition to alternative fuels is an important step towards the use of pure hydrogen as an automobile fuel, i.e. the creation of hydrogen electric vehicles with fuel cells and electric drives. In this case, toxicity of emissions can be decreased dramatically (2-4 times) with the operating consumption of hydrocarbon fuel being reduced by 35-40% and operating efficiency increased by 20-25%.

Table 1. The properties of hydrogen (at 273.16 K or 0°C)

Parameters	Values
Density, g/l at normal pressure at 2.5×10^5 atm. at 2.7×10^{18} atm.	 0.08987 0.66 1.12×10^7
Higher heating value, kJ/kg	141 800
Melting point, °C	–259.14
Boiling point, °C	–252.5
Critical temperature, °C	–239.92 (33.24 K)
Critical pressure, atm.	12.8 (12.80 K)
Specific heat, J/(mol·K)	28.8 (H_2)
Combustion temperature, K Burn rate, cm/s (laminar flame of air mixtures at standard conditions)	2300 300
Quenching distance, mm	0.6
Auto-ignition temperature, K	850
Ignition energy, mJ	0.018
Ignition interval for air mixtures, % vol.	4-75
Relative heat of combustion vs. gasoline, per 1 kg	2.75

Absence of technologies for the production of alternative high hydrogen content fuels hinders fuel and energy complex (FEC) restructuring towards a more sustainable and diversified energy supply of economy and to the mitigation of industry, transport and energy impacts on the environment.

The technology for the production of methane-hydrogen mixtures (MHMs) in the process of adiabatic methane conversion (AMC) has been developed and experimentally tested. The AMC technology as applied to heating from a high-temperature gas-cooled reactor (HTGR) forms an innovative basis for energy technologies of processing natural gas into highly efficient energy carriers.

The AMC technology essentially simplifies the industrial process: it requires neither oxygen production nor energy- and cost-consuming water electrolysis, and occurs at lower temperatures (less than 700°C) and applies technology solutions, processes and catalysts that are well-proven in the high-tonnage chemistry.

In compliance with this technology the end product, i. e. methane-hydrogen mixture, is to be manufactured not through mixing natural gas with pure hydrogen produced in a separate unit but rather through one-stage AMC, which can essentially simplify and reduce the cost of the production.

The process installation efficiency depends largely on the main and auxiliary equipment weight and dimensions as well as the general process flow. It is not only the installation process flow that is important but also its energy component, which enables smoothly to take advantage of high process performance in an optimal way.

The experience of industrial introduction of the two-stage TANDEM steam-oxygen conversion and of the AMC process development as applied to an MHR-T high-temperature helium reactor was taken into account in working out the technology concept.

Energy intensity ratio was selected as a feasibility criterion for the production of methane-hydrogen mixtures.

The AMC process is used for the production of methane-hydrogen fuel mixtures from natural gas with reduced energy and material costs as compared to traditional methods.

The raw material used for the manufacture of the above product is natural gas, and the energy carrier includes flue gases of natural gas combustion products. Finished production is a methane-hydrogen mixture containing 48% hydrogen compressed to a pressure of 2 to 7 MPa.

For the natural gas based production of MHMs without external energy sources in the AMC process, the output of MHMs with a hydrogen content of 48% amounts to 1800 m^3 per 1000 m^3 of natural gas.

Methane-Hydrogen Mixture Production Process

The energy and process flow of methane-hydrogen mixture production includes engineering solutions aimed at achieving minimum energy consumption and maximum performance.

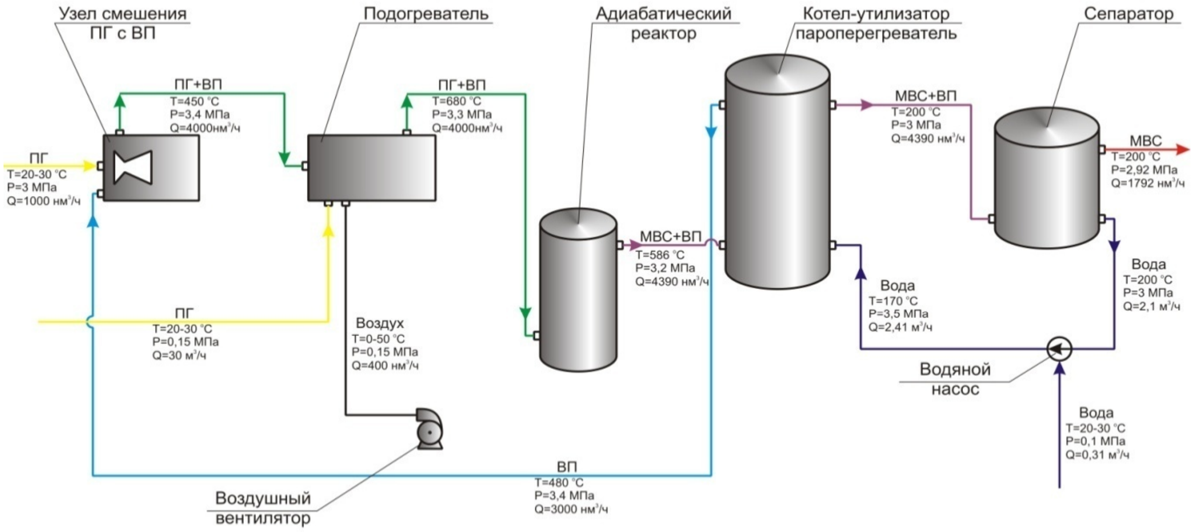
Fig. 1 shows the MHM production process flow.

Natural gas purified from sulphur compounds enters the mixing unit to mix with water steam from the waste heat boiler. Natural gas mixed with water steam at about 450°C proceeds to the fired heater. The fired heater output line delivers mixture of about 680°C to the adiabatic reactor. During the adiabatic methane conversion process in the reactor, methane-hydrogen mixture and water steam with a temperature of about 590°C are produced. As the adiabatic reactor water is partially used to produce hydrogen, it is to be constantly replenished. Before entering the system, the water is to pass through the filter.

All natural gas, methane-hydrogen mixture, steam and water flow rates are indicated in the diagram.

At the existing gas compressor stations (GCS) and those under construction with gas pumping units (GPUs) subject to modernisation, the use of methane-hydrogen mixtures with high hydrogen content (up to 50%) as fuel gases will both significantly improve performance and reduce the fuel gas consumption and emission indices.

Such work should involve different functional designs of replacement units with the simultaneous high level of unification of MHM production blocks targeted to most massive representative projects.



ПГ - природный газ
МВС - метаново-водородная смесь
ВП - водяной пар

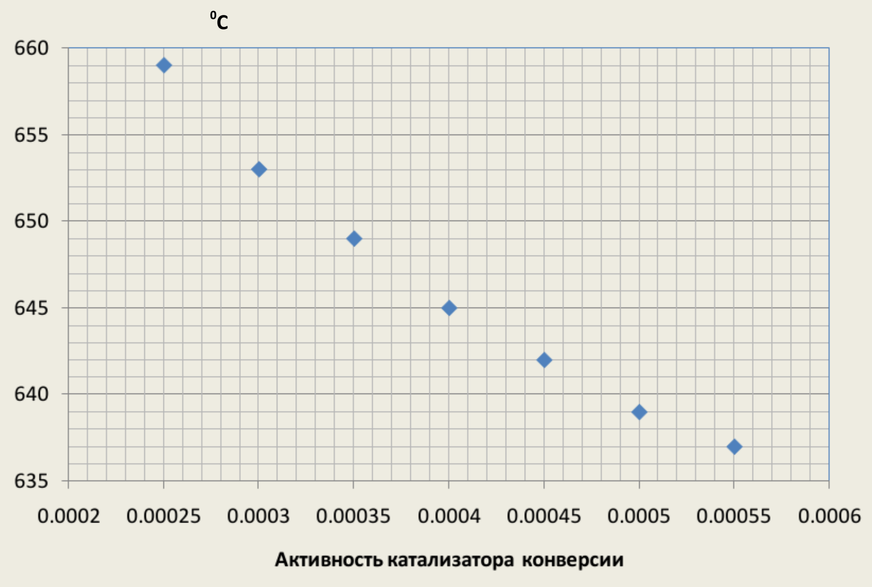
Узел смешения ПГ с ВП	NG and WS mixing unit;
ПГ+ВП, T=450°C, P=3,4 МПа, Q=4000 нм^3/ч nm^3/h;	NG+WS, T=450°C, P=3.4 MPa, Q=4000
ПГ, T=20-30°C, P=3 МПа, Q=1000 нм^3/ч	NG, T=20-30°C, P=3 MPa, Q=1000 nm^3/h;
ПГ, T=20-30°C, P=0,15 МПа, Q=30 м^3/ч	NG, T=20-30°C, P=0.15 MPa, Q=30 m^3/h;
Подогреватель	Heater;
ПГ+ВП, T=680°C, P=3,3 МПа, Q=4000 нм^3/ч nm^3/h;	NG+WS, T=680°C, P=3.3 MPa, Q=4000
Воздух	Air;
T=0-50°C, P=0,15 МПа, Q=400 нм^3/ч	T=0-50°C, P=0.15 MPa, Q=400 nm^3/h;
Воздушный вентилятор	Air fan;
Адиабатический реактор	Adiabatic reactor;
МВС+ВП, T=586°C, P=3,2 МПа, Q=4390 нм^3/ч nm^3/h;	MHM+WS, T=586°C, P=3.2 MPa, Q=4390
Котел-утилизатор пароперегреватель	waste heat boiler / superheater;
МВС+ВП, T=200°C, P=3 МПа, Q=4390 нм^3/ч nm^3/h; Сепаратор	MHM+WS, T=200°C, P=3 MPa, Q=4390 separator;
МВС, T=200°C, P=2,92 МПа, Q=1792 нм^3/ч	MHM, T=200°C, P=2.92 MPa, Q=1792 nm^3/h;
Вода	water;
T=200°C, P=3 МПа, Q=2,1 м^3/ч	T=200°C, P=3 MPa, Q=2.1 m^3/h;
Вода	water;
T=20-30°C, P=0,1 МПа, Q=0,31 м^3/ч	T=20-30°C, P=0.1 MPa, Q=0.31 m^3/h;
Водяной насос	water pump;
Вода	water;
T=170°C, P=3,5 МПа, Q=2,41 м^3/ч	T=170°C, P=3.5 MPa, Q=2,41 m^3/h;
ВП, T=480°C, P=3,4 МПа, Q=3000 нм^3/ч	WS, T=480°C, P=3.4 MPa, Q=3000 nm^3/h;
ПГ – природный газ	NG – natural gas;
МВС – метаново-водородная смесь	MHM – methane-hydrogen mixture;

ВП – водяной пар	WS – water steam.

Fig. 1. Schematic diagram of an AMC-based methane-hydrogen mixture installation

Fig. 2 presents a diagram of changing the required temperature of methane conversion into methane-hydrogen mixture against the catalyst activity to obtain a final hydrogen dry mix content of 42-48% (by volume). As you can see from the diagram, with the catalyst activity increasing only twice as much, the methane conversion temperature is reduced by 25 degrees.

In this installation, the natural gas input of 1000 nm^3/h will produce 1792 nm^3/h of methane-hydrogen mixture at the output.

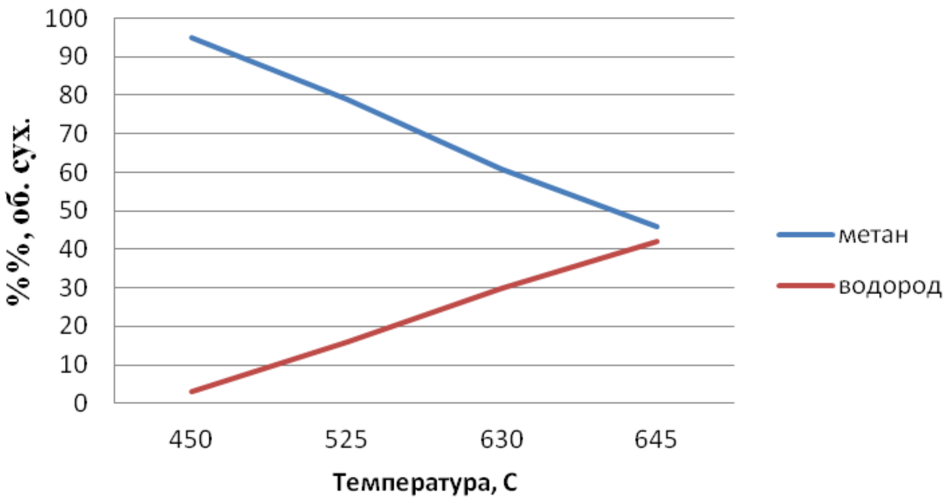


Активность катализатора конверсии	Conversion catalyst activity

Fig. 2. The required methane conversion temperature in MHMs (°C) against the catalyst activity

Thus, in accordance with the calculations, conversion temperatures of methane in MHMs fall within the range of 637°C to 659°C depending on the activity of the catalyst employed. As the catalyst activity is an empirical value and may both differ from the assumed figures and decrease during the operation, the possibility of heating the steam gas mixture (SGM) is provided for. The SGM incoming for the conversion can be heated up to temperatures higher than the design value.

The hydrogen content in MHM can vary from 0 to 44-48% both by changing the heating temperature of the steam gas mixture (Fig. 3) and by diluting a ready MHM with natural gas.



%%, об.сух.	%%, dry vol.
метан	methane
водород	hydrogen
Температура, С	Temperature, C

Fig. 3. Change of the hydrogen and methane content in MHMs as a function of the temperature of steam gas mixture heating

By increasing the MHM hydrogen content, with a relatively small decrease of the Wobbe index, we can considerably reduce CO_2 emissions through the withdrawal of carbon dioxide during the AMC (Table 2). As set forth in Table 2, with the MHM hydrogen content of 48% (by volume) the relative CO_2 emission amounts to 76%.

Table 2. Wobbe index and relative CO_2 emission values as functions of the MHM hydrogen content

MHM (H_2 content [% vol.])	**Relative Wobbe index [%]***	**Relative CO_2 emission, %**
0	100	100
10	97.4	96.65
20	94.7	92.73
30	92.0	88.00
40	89.3	83.28
60	84.2	68.86
80	80.4	45.33
100	85.0	0

* The Wobbe index (W) is defined as $W = HHV_{h2} / \sqrt{d}$, where HHV_{h2} is the higher heating value, MJ/m^3, d is the gas density, kg/m^3.

Application of MHMs as fuels for the gas turbine equipment

Methane-hydrogen mixture produced can be used as a gas turbine drive fuel. The components of the feedstock, i. e. natural gas, and the sales gas outgoing from the MHM installation are set forth below (Table 3).

Table 3. Feedstock and efflux components in the AMC process to produce MHMs

Volume components, % vol. (wet)	feed	efflux
	Natural gas	Methane-hydrogen mixture (wet)
Carbon dioxide, CO_2	0.065	3.262
Carbon monoxide, CO	0.000	0.233
Hydrogen, H_2	0.000	13.621
Nitrogen, N_2	0.780	0.145
Argon, Ar	0.000	0.000
Water, H_2O	0.000	67.694
Methane, CH_4	98.836	15.045
Ethane, C_2H_6	0.242	0.000
Propane, C_3H_8	0.055	0.000
Butane, C_4H_{10}	0.016	0.000
Pentane, C_5H_{12}	0.006	0.000
Total	100.000	100.000

The feedstock (natural gas) is basically composed of methane (99%). The effluent product is a mixture of three components: water steam (67.7% vol.), hydrogen (13.6% vol.) and methane (15%). The following components have an increased content as compared to the feedstock: carbon dioxide (3.3%) and carbon monoxide (0.233%). However, CO_2 and CO emissions are a third less where the MHM is used as a fuel gas. This occurs due to the fact that some of the MHM-contained hydrogen is produced from water, and the amount of fuel gas used is reduced by 30-40%.

Where heat recovery modules based on the MHM-producing AMC are installed at compressor or power stations with modern gas turbine units (GTUs), the efficiency can be increased over 50%, even without the use of steam power plants or regenerative heating. In case of using thermal heating loads, the gas capacity utilisation can be increased up to 60-62% with a sharp drop of NO_x emission values below 10-25 ppm (20-50 mg/m^3) and the elimination of HCN (hydrocyanic acid) and ethylene emissions.

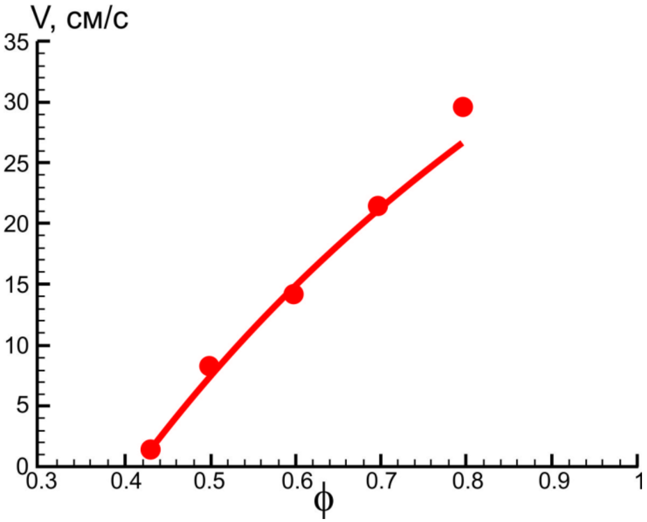
In the recent 10-15 years, national and foreign gas turbine firms have been engaged in the intensive work on the development of combustion chambers with burning of premixed fuel-air mixtures with the air excess factor (α_{fr}) in the combustion zone being up to 1.9-2.5. By the implementation of this method, almost all leading gas turbine firms obtained the concentration of nitrogen oxides not higher than 8-25 million^{-1} (O_2=15%) for their combustion chambers under operating mode.

However, during the trial and operation of combustion chambers burning “poor” homogeneous fuel-air mixtures serious problems arise regarding their operational reliability and guaranteed performance in terms of harmful emissions.

The hydrogen component in the methane-hydrogen fuel is to remove restrictions on the fuel-air mixture composition and to increase the combustion stability of “super-poor” mixtures.

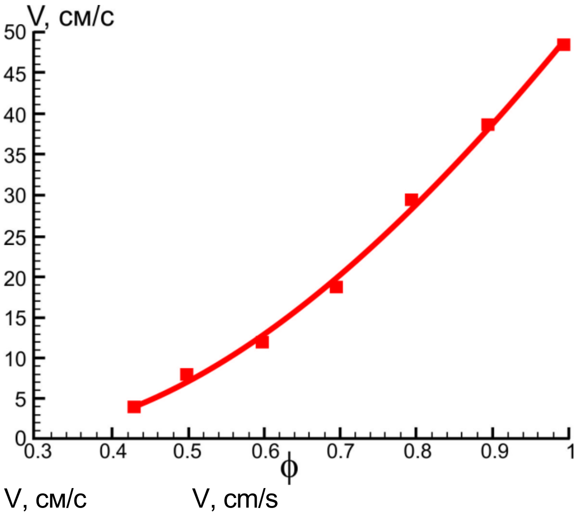
It is also important that high hydrogen content (up to 40-44%) in the methane-hydrogen fuel can decrease fuel carbon index and reduce emissions of carbon dioxide and other greenhouse gases.

Experiments conducted in 2011 demonstrated that the addition of hydrogen to methane can expand its combustion limits. In particular, addition of 10% hydrogen entailed the mixture flammability with fuel-air equivalence ratio j = 0.43 (Fig. 4). If a hydrogen-free mixture ignited only at an initial pressure of 10 atm., the addition of 20% hydrogen produced stable mixture combustion at normal pressure (Fig. 5).



V, см/с V, cm/s

Fig. 4. Normal combustion rate of the methane-hydrogen mixture (10% H_2 + 90% CH_4) at P_0 = 1 atm. and T_0 = 22°C against the fuel-air equivalence ratio j *.*



V, см/с V, cm/s

Fig. 5. Normal combustion rate of the methane-hydrogen mixture (20% H_2 + 90% CH_4) at P_0 = 1 atm and T_0 = 22°C against the fuel-air equivalence ratio j *.*

As shown in Fig. 6, the MHM burns steadily even with a high water steam content (20-30%). This allows using water steam to reduce emissions and increase gas turbine power and efficiency. The model calculations and experimental data prove that the maximum concentration of nitrogen oxides and carbon decreases with the increase of water steam content.

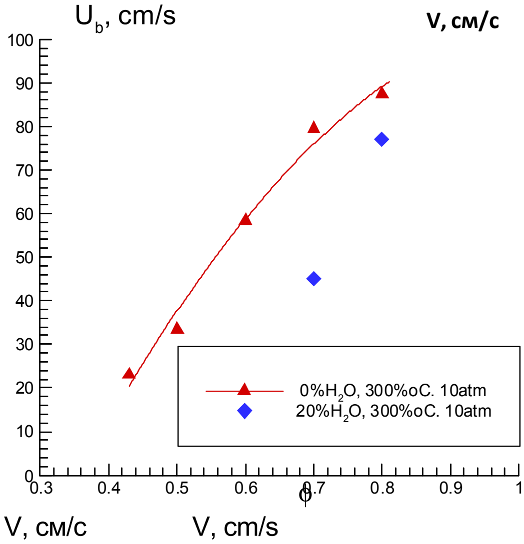


Fig.6. The effect of adding 20% water steam the mixture (20% H_2 + 80% CH_4) on the normal rate of combustion in the air at *P* = 10 atm and T_0 = 300 °C

For low power gas turbine units (GTUs), it is technologically difficult to create highly efficient turbo-machines and to arrange effective cooling systems for hot component parts of gas turbines. The use of MHM proves to be the most reasonable when modernising such machines.

Shifting to MHM for units with a relatively low initial efficiency ratio can increase the gas usage efficiency by 20-25% and reduce NO_x emissions by more than an order of magnitude.

New gas compressor units (GCUs), structurally differing from the former drives and complying with the present-day operational requirements, are created in compliance with the latest gas industry standards to be used during the reconstruction of existing compressor stations of OAO Gazprom (JSC) and construction of new ones.

All turbine modernisation programs, in particular those for the creation of state-of-the-art GCUs, invariably provide for high efficiency, reliability and environmental safety of new facilities.

The basic task of modernisation is to provide the required gas flows. Thus, it is desirable to install gas compressor units of increased unit capacity. For a pipe of 1420 mm in diameter with a daily gas flow of 90-95 million m^3, the average capacity of all related GCUs amounts to 80-85 MW.

The MHM Use Effectiveness in Gas-Turbine Units

For new powerful GCUs, the use of MHM, depending on design solutions can reduce gas consumption by 8-16% and NO_x emissions below 25 mg/nm^3. The use of hydrogen and MHM for the production of electric energy with GTUs is also highly efficient.

So far the maximum unit capacity of GTUs has reached 300 MW; the power island mode efficiency amounts to 36-38%. The efficiency of multi-shaft gas turbines, which are built on aircraft engines with high compression ratios, can reach 40% or more, with the initial temperature of gases being 1300-1500°C and the compression degree of 20-30.

"Low toxicity" natural gas burning has been adopted in GTUs. This technique is most effective in combustion chambers utilising pre-mixed homogeneous gas-air mixture at high air excess levels (cc=2-2,1) and relatively low (1500-1550°C) and uniform flame temperature. With such a burning technique, the formation of NO_X can be restricted to 20-50 mg/m^3 under normal conditions (normally, they imply 15% oxygen content in combustion products) with high efficiency of combustion (CO<50 mg/m^3). The problem is to maintain the combustion stability and conditions close to optimal ones in the event that the combustion behaviour changes.

The above-stated proves that resources of further combustion process improvement have been virtually exhausted, and the prospects for enhancing economic and environmental performance of gas turbine engines (GTEs) should be associated with the use of hydrogen combined with methane or any other low cost fuel.

It is stated following the national study, including that by the Institute of Chemical Physics of the RAS, that there is no way to radically solve the problem of transiting to poor combustion while using homogeneous (perfect) mixtures: stable ignition of such mixtures is just not possible in low load modes of a specific gas turbine combustion chamber, irrespective of its structure. This statement can also be proved by the data available on the expansion of effective poor limit for imperfect mixing. At the same time, the results obtained indicate that the performance of the combustion process using hydrogen as a fuel or its component (together with a hydrocarbon fuel) can be dramatically improved. Building an optimal combustion process with the use of hydrogen as an addition to the basic (hydrocarbon) fuel is to be studied, and it will remain urgent in the near future due to the environmental advantages of hydrogen. In the context of the general trend of rising oil prices, special emphasis is given to the study of combustion and development of gas turbine engines running on hydrogen and methane (hythane) mixtures. Where heat recovery modules based on the MHM-producing AMC are installed at power stations with state-of-the-art gas turbine units (GTUs), the efficiency can be increased over 50%, even without the use of steam power plants or regenerative heating. In case of using thermal heating loads, the gas capacity utilisation can be increased up to 60-62% with a sharp drop of emission values to 10-25 ppm (20-50 mg/m^3).

In addition to a gas turbine, it is appropriate to include a waste heat boiler and a direct-contact condenser into the installation. The heat of the exhaust gases leaving the turbine is utilised in a heat exchanger to heat the steam gas mixture. The latter is used to produce a water steam and methane-hydrogen mixture, which is injected into the combustion chamber, with a certain portion being fed to cool the gas turbine components. Water steam is condensed from the exhaust gases, and the condensed fluid is fed to the process. The overall utilisation factor of the fuel gas heat can be increased up to 75-80%.

The utilisation of the flue gas heat is one of the main ways of increasing the efficiency of gas turbine units, and the work in this area is very intensive today. Existing cogeneration plants and combined-cycle gas turbines can significantly increase fuel energy efficiency. Unique Vodoley contact combined steam/gas turbine units with the cycle including water generation have been developed and are available for delivery. Such installations can be further improved to reach a higher degree of exhaust gases heat recovery. In this connection, the efficient use of thermochemical heat recovery technologies offers the greatest promise. These technologies provide the methane-hydrogen fuel that has a number of advantages. The integration of Vodoley technologies and the low-temperature steam conversion of methane will enable to build a new type of a gas turbine with high energy and environmental performance (Tandem technology), based on the experience of using hydrogen-bearing gases as a fuel for GTUs (Fig. 7).

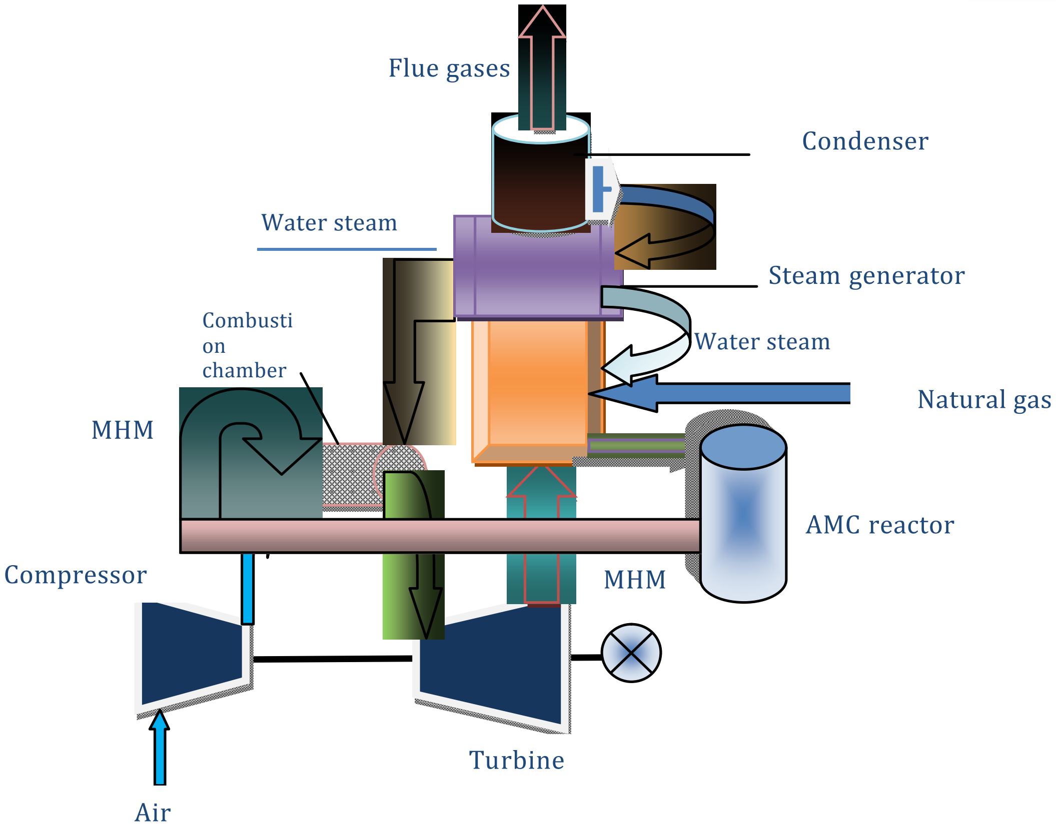


Fig. 7. Configuration of a GTU running on MHM (Tandem technology)

According to the data available, the analysis of Tandem gas turbine performance shows that the installation capacity increase as compared to the base GTU can amount up to 70-80%, with the decrease in fuel consumption of as much as 35-40%, and a simultaneous sharp drop in NO_x emission (4-8 times).

Application of MHM in the Energy Industry

In the production of heating with the use of boiler units, high-quality combustion of natural hydrocarbon fuels is only possible in a very high-intensity combustion process. The intensification of liquid fuel burning enables complete combustion at an almost stoichiometric air-fuel ratio (air excess factor ~ 1.0), whereas the air excess factor of 1.15-1.25 is considered normal for conventional power plants. The boiler unit efficiency increases by 1% as the excess air factor decreases by 0.1%. Calculations show that only the decrease in the air flow rate of burners from 1.2 to 1.05 for chamber furnaces with flue gas temperature of 400-500°C would ensure at least 15-20% fuel savings, i. e. several times as much as the energy consumption for the natural gas conversion to produce MHM. During the combustion of MHM instead of fossil fuels, the energy is not only used to improve the fuel quality but also to turbulise the flare and improve the flared media mixing.

This advantage is obtained through improving the fuel quality and affecting the fuel flare as well as due to hydrogen properties. It allows using highly watered substandard liquid fuel and oily wastes with mechanical impurities of up to 2 mm as additives to the prime gas fuel, and increasing the boiler efficiency at least by 2-3% through the reduction of effluent gas heat losses, heat exchange intensification and air excess factor reduction. At nominal operating conditions of the boiler, emissions of nitrogen oxides can be reduced by up to 70%.

Application of MHM in the Transport Industry

Transition to alternative fuels is an important step in the pure hydrogen application as a fuel for motor vehicles, i. e. the creation of a hydrogen electric vehicle with the fuel cell and electric drive. In this case, efficiency of the hydrogen-powered propulsion system for the urban driving cycle (with numerous stops and braking and acceleration patterns) can reach 50-55%, which is nearly 2-2.5 times as much as the efficiency of gasoline internal combustion engines. In addition, complete absence of harmful emissions is ensured.

Pilot operation of alternative fuel motor vehicles in Russia and abroad has demonstrated that the transition of motor vehicles to the methane-hydrogen mixture with a hydrogen content of 5% to 10% by weight (20% to 40% by volume) is promising. Moreover, the toxicity of emissions is dramatically decreased (2-4 times), operational consumption rate of hydrocarbon fuel is reduced by 35-40%, and operational efficiency is increased by 20-25%.

While the transition of motor vehicles to natural gas ensures compliance with Euro 3 and (with the use of new upgraded engines) Euro 4 standards, methane-hydrogen mixtures (MHM) with the hydrogen content of at least 20% comply with Euro 4 even for existing engines and, provided that the hydrogen content in the mixture increases to 44-48% (MHM-type mixtures), these mixtures will meet Euro 5 standards.

The effectiveness of reducing hazardous emissions through using methane-hydrogen mixtures (MHM) is higher than in case of the use of hydrogen of comparable volume. The point is that in case of transiting, for example, 10% of the vehicle fleet to pure hydrogen (reducing emissions to almost nil), the overall reduction of the entire fleet emissions amounts to 10%, whereas in case of using MHMs with the hydrogen content of 10% by weight for all the fleet vehicles the overall reduction of the entire fleet emissions amounts to 50%, i. e. the hydrogen usage effectiveness increases fivefold.

As opposed to the hydrogen used in fuel cells, where impurities (especially carbon monoxide) are rigidly restricted and the required purity can reach up to 99.9999%, in MHM-type mixtures such purity requirements are not so stringent, as most of the impurities being the fuel components will be burned during the basic combustion process of the engine.

MHM-Based Industrial Technologies

The initial feed gas composition will be normalised in the process of adiabatic methane conversion with the transformation of higher methane homologues into hydrogen. This allows us to consider the process of obtaining MHMs as an effective means of diversifying gas industry to produce an alternative gas fuel of normalised composition out of various raw sources, including gas condensates, associated gases, coke oven gases, shale gases and other sources of gases of non-normalised composition.

Moreover, MHMs with high hydrogen content allows using these mixtures as an efficient fuel for the installations for direct electrochemical energy generation in high-temperature solid oxide fuel cells (SOFC) with efficiency up to 60% in the mode of electric power generation and up to 80% in the heat and electricity cogeneration mode. This technology paves the way to future sectors of the so-called Hydrogen Economy.

In 2007-2011, an important large-scale experiment took place on the island of Ameland (Netherlands). In the course of this experiment, methane-hydrogen fuel with the hydrogen content of up to 20%, being supplied to public utility system consumers, has shown no deviation from the accepted natural gas regulatory standards.

Methane-hydrogen fuel can be further converted into a syngas for use in gas chemical processes (GTL) or hydrogen can be extracted from the fuel as the target product for various industries using either PSA methods (pressure swing adsorption) or heavy-tonnage membrane technologies adopted in the international practice.

Such manifold MHM application as an alternative gas fuel consisting of methane and hydrogen allows considering these technologies as a single technology platform of centralised gas fuel production not only for its local and regional application spheres but also for supplying through particular energy corridors into transnational gas transmission networks and stockpiling of the fuel in underground gas storage facilities (UGS).

In the AMC process, carbon dioxide (CO_2) can be easily extracted at high pressure, thus an effective support of CCS (carbon sequestration system) mechanisms and technologies, ETS (emissions trading system) tools, including within the framework of the EU “Road Map” in the power supply sector, can be expected until 2050.

Conclusions

1. Natural gas is a key carrier in the global energy industry of the 21st century. Its role is increasing from year to year due to its operational peculiarities. Over the longer term, hydrogen fuel is to replace natural gas. Hydrogen is the most efficient and environmentally friendly fuel.

2. In Russia, the adiabatic methane conversion (AMC) technology has been developed for the production of the methane-hydrogen fuel (MHM) with a hydrogen content of up to 48%. This technology essentially simplifies the process of industrial hydrogen production as it does not require the oxygen production and occurs at lower temperatures (up to 680°C).

3. The experiments demonstrated that the increase in the hydrogen content of the MHM:

- expands its combustion limits;
- ensures stable burning of the mixture even at normal pressure;
- enables combustion with a considerable water steam content (20-30%);
- allows for a considerable reduction of CO_2 emissions through the carbon dioxide withdrawal during the AMC process, with a relatively small Wobbe index decrease.

4. The integration of technologies for flue gas heat utilisation and low-temperature adiabatic methane conversion will enable to build a new gas turbine type with high energy and environmental performance (Tandem technology). The capacity of such gas turbine unit as compared to the base GTU can increase up to 70-80%, with the decrease in fuel consumption of as much as 35-40%, and a simultaneous sharp drop in NO_x emission (4-8 times).

5. The MHM production technology developed permits:

- to consider the process of obtaining MHMs as an effective means of diversifying the gas industry to produce an alternative gas fuel of normalised composition out of various raw sources, including gas condensates, associated gases, coke oven gases, shale gases and other sources of gases of non-normalised composition;
- to use MHMs as an efficient fuel for the installations of direct electrochemical energy generation in high-temperature solid oxide fuel cells (SOFC) with efficiency up to 60% in the mode of electric power generation and up to 80% in the heat and electricity cogeneration mode. This technology paves the way to future sectors of the so-called Hydrogen Economy, including motor vehicle transport having practically nil emissions;
- to consider these technologies as a single technology platform of centralised gas fuel production not only for its local and regional application spheres but also for supplying through particular energy corridors into transnational gas transmission networks and stockpiling of the fuel in underground gas storage facilities (UGS);

- to receive effective support of CCS (carbon sequestration system) mechanisms and technologies, ETS (emissions trading system) tools, including within the framework of the EU "Road Map" in the power supply sector, until 2050.