Climate and Environmental Backgrounds of Fuel Utilization, Influencing upon Alteration the European and Ukrainian Trends of Gas Supply. Part 1. Present requirements to selection the gas fuels. Thermodynamic evaluation the principal characteristics of gas fuel

The work examines the starting points on the formation of fuel markets in Europe within the framework of the concept of sustainable development of the countries’ economics, taking into account the main limitations, primarily the climatic and environmental consequences of fuels combustion. This approach has led in the past years to simultaneous increase in absolute volumes’ consumption of mineral (organic, carbon-rich) fuel’s flow rate and to reduction of their shares in the overall fuel balance. The relevant changes had occurred because of simultaneous production and consumption the alternative fuels, including renewable gas and energy sources.

New schemes, methods and ways of fuel supply have been analyzed, including maritime transportation of liquefied fuels (liquefied natural gas LNG, liquid hydrocarbons LPG, ammonia NH₃) along with creation of a modern tanker fleet with floating and land-based regasification and gas storage (FSRU) systems; systems of interconnecting the pipelines for fuel supply, including hydrogen-enriched natural gas (HENG).

According to the cultivated opinion, the global warming is considered as a consequence of the carbonization of environment due to emission of C-rich combustion products (CO₂) into the atmosphere.
The specified contribution of CO₂ to atmospheric pollution is caused by the insufficient efficiency of fuel use, for example, in heating furnaces (up to 40 % of the total amount of fuel consumed in the industry is burned in furnaces). If the emissions value of a conventional natural gas combustion systems in furnaces meets the level of emissions up to 0.45 kg CO₂/kWh, then in the case of equipping the furnace with an efficient waste gas heat recovery system, the emissions are reducing to 0.2–0.25 kg CO₂/kWh, (Wunning J.). The determinant role of the efficiency of fuel use \( \eta \) has been correlated with the scale of atmospheric pollution with greenhouse gases (CO₂) emission by means of thermodynamic analysis of energy efficiency. The efficiency of fuel utilization: by enthalpy \( \eta_H \) and by exergy \( \eta_{eff} \) — has been computed for the cases of burning the widespread fuels and the comparative analysis has been performed. The calculations of thermal energy characteristics of the fuels have been carried out by using the original author’s methodology based upon assumption of equilibrium thermodynamics for the cases of using the widespread gas fuels within the temperature range \( T \) from the standard \( T_0 \) to the theoretical combustion temperature \( T_T \).

In accordance with original author’s method the most important heat engineering characteristics of the fuels have been studied by means of approaches of equilibrium thermodynamics. Higher and lower combustion heat, higher and lower Wobbe numbers, theoretical (adiabatic) combustion temperature of the widespread fuels have been determined. An influence of hydrogen content in CH₄/H₂ gas fuel mixtures on the mentioned properties has been determined.

From the list of firing engineering characteristics, the formation of the methane number MN for different organic and alternative fuels have been considered. The accumulated numerical values of MN for the widespread types of fuels have been stated and compared. Bibl. 38, Fig. 4, Tab. 1.

**Keywords:** decarbonization, efficiency of fuel using, fuel market, heat recovery, heat value (high and low), hydrogen, methane number MN, renewable energy, thermodynamic analysis, total enthalpy.

### Introduction

The structure of the country’s fuel balance should be connected and coordinated with the current state and the features of national economics including the value of complete fuel consumption. It means that the structure of the fuel balance of Ukrainian economics, which is characterized by a raw material basis and of multiton large — capacity production, with predominant energy consumption in the primary — processing branches of industry, cannot be similar to the distribution of energy sources and certain types of fuel used in the small and medium-sized European countries with mainly high-tech low-tonnage industry.

A widespread trend of recent years in energy and fuel supplying makes an increase of the share of alternative fuels, in particular — of renewable energy sources, compared to mineral (organic, fossil) fuels. A significant place in the relevant plans belongs to expansion the volumes of manufactured “green” hydrogen, which is produced using the renewable energy sources (“green energy”): sun, wind, low-carbon fuels, separate biofuels [1–3].

The special place takes the problem of LNG (liquefied natural gas) supplying, including bio-LNG, from USA and Russia — to European market(s), particularly through the floating storage and regasification units (FSRUs) [4].

At the same time, for European and Ukrainian conditions, the reasons for these trends are quite different. If for the situation in the EU the main task constitutes the prevention of climate changes through decarbonization of the environment, then for Ukrainian realities the structure of the fuel balance is determined by the purpose of reducing the complete fuels’ consumption and the limitation the sources of its supply, as well as by political and economic reasons. The proper requirements should be performed including an ensuring the international agreements on the intended taxation of emissions of carbon-containing compounds to atmosphere in the nearest future [1–3, 5–8].

The discrepancy is observed at present in the most of f countries — between real distribution of traditional widely used fuels — carbon-containing ones (mainly — fossil fuels), providing the supply of national economics, with much lower share of
perspective renewable fuels and energy sources. Despite the recognition of the expediency of advancement the renewable energy sources and on the prospects for the use of alternative fuels with the purpose of the fossil fuels' saving for the future human generations and the decarbonization of the environment, till last time the perspective plans on using the traditional fuels were absent. For all this there was no consensus on middle — and long-term development plans on advancement the gas industry and natural gas market, as well as regarding the structure of fuel consumption by separate sectors of economics and regarding the branches of industry. Mentioned situation took place in the 2020-th, before the recent events in Ukraine when the change in economic relations between the Russian Federation and the EU has happened. Breach of treaty regarding the natural gas pipeline supplying to the European markets has arisen in 2022 [4].

In some advanced countries, firstly in Germany, an attention is focused upon a large-scale implementation of hydrogen as a fuel and the process agent in the steelmaking industry. Mentioned approach is undertaking in frame of climate change mitigation activity and decarbonization [9]. Particularly, Thyssenkrupp Steel with SMS group, Dusseldorf, are engaged in creation and erection the first H₂ — powered DRI (direct reduction iron) plant. Accordingly this project — one of the biggest worldwide — a lowering of the Germany’s total CO₂ emission with corresponding reduction of effluents 3.5·10⁶ t CO₂/year — is presumed.

German group of companies ThyssenKrupp will be the first steel — maker in the world to combine 100 % H₂ capable DRI plant with the melters: two melters of innovative design are arranged adjacent to the DRI plant with production of the molten iron immediately [9].

Comparative evaluations were reduced to conclusion that the most acceptable method of production the hydrogen is steam reforming of methane (natural gas) [1, 10], which remains the principal technological process provided with perfect technology regulations during next 10 years (2030) [10]. Appropriate production facilities for the production the hydrogen, which is called “blue hydrogen”, must be combined with the equipment and the processes of CO₂ removal with provision its storage (the process of “carbon capture and store (CCS)”) [1, 10]. Without the last technology component, CO₂ emissions per unit of fuel energy are 40 % higher than the corresponding value during direct combustion of natural gas (according to the conclusions of K. Cocain and M. Kochran [10]). It should be noted that for the technology of the biofuels processing and by biomethane production of vegetable raw materials (for example, the processes of collecting the landfill gas). For example, the processes of refinement the biogas of CO₂ by means of carbon dioxide separation or absorption make one of the most essential stages of biomethane production [11].

This paper represents the 1st part of the work. In its turn, the paper is divided into two sections:

Section 1 — State-of-the-art;
Section 2 — Thermodynamics of using fuels and comparative evaluation of gas fuels.
Both sections are divided into following paragraphs:

Forming of fuel markets by nomenclature and structure;
Main gas fuels at European markets;
Novel ways of supplying the natural gas, interconnection the networks and liquefied fuels' maritime transport;
Efficiency of fuel using as an impact-factor of reduction the carbon emission (decarbonization of environment);
Principal characteristics of the gas fuels.

Methods and technique of calculation the basic data.

Section 1. State-of-the-art

1. Forming the markets of power generation sources and proper fuels (usually — fossil fuels) as well as selection the fuels, supplying other markets, presents a result of political, economical and environmental efforts of the governments and of the public organizations’ activity in different countries within the separate world regions under consideration. The European fuel market of the last period has become the system structure, changed in significant degree by influence of the current trend for decarbonization of environment.

Mentioned tendency in combination with the statement, relevant to minimization of using the organic (fossil) fuels, serves for saving the mineral fuels for the future human generations.

The task of substitution the natural gas (NG) for alternative fuels nowadays is solved by means of using the methane-hydrogen mixtures (MG—mixed gases) with an injection the hydrogen into
the local NG pipelines [1–3]. By testing the hydrogen-based gas distribution network supplying the 100 % H₂-containing fuel, the microgrids are using [12]. Particularly, over funding of the Ministry for Economic Affairs and Energy (BMWi, Germany) the testing of the mentioned transport system has been foreseen and realized [1].

2. During the last half a century the structure of the energy’s and fuel’s sources and markets has undergone a great transformation. Indicated 50–60 years represent insignificant time portion against a background of the humanity’s history. For the space of previous centuries, particularly during XVIII–XX centuries, the mineral and process (technological) fuels — mainly produced of coal — were supplied with the former markets to the industrial and municipal consumers. Till 2010–2015 the Ukraine took the first places in Europe with production and using of blast furnace and coke-oven gases [13]. The town gas in Germany produced using coal gasification was composed of up to 60 % hydrogen in addition to CO, CH₄ and N₂ [1]. Using of town gas during more than 50 years the Walter Dreizler GmbH has gained the proper experience of operation with hydrogen of high percentage [1].

To provide the limitation of global environment’s warming less than 1.5–2 °C, the world community has decided to prevent atmospheric carbonization (2015, Paris). Particularly, the European Union (EU) is going to ensure the problem’s solution with 80–95 % decrease of emission of greenhouse gases to 2050 with due to reducing of consumption or complete exclusion of using the fossil fuels [8].

Reducing of greenhouse gases’ emission, by covering of 27 % of total required energy consumption with renewable sources, has been envisaged in EU [8]. Simultaneously with reduction of greenhouse gases’ emission, an enhancement of energy efficiency of fuel using in different branches is expected [3, 8].

The present period is distinguished oneself by unstable characteristics of the energy sources and of the fuels’ supplying markets. By this reason the above mentioned international and EU statements could be revised while their fulfillment will be delayed or completely canceled.

Germany already has postponed the plans to close all its nuclear power plants. It would keep at least two of its three remaining facilities on standby until the middle of 2023 [4]. Germany has announced that would increase its consumption of coal-fired power in an effort to avoid an energy crisis. The reduction in gas and power demand as well as an increase in LNG imports have become crucial in the EU energy strategy [4].

3. The combustion processes, on the one hand, and the weather conditions, global and local climate of environment, on the other hand, are in the strong and physically grounded interdependence [14, 15]. The temperature and moisture of an ambient air, atmospheric pressure, wind direction and the velocity of wind are influencing parameters for the fundamental fuel’s burning rates, the flames formation and the combustion process stability [16, 17]. Mentioned parameters’ impact for the state of combustion process, pollutants (NOₓ, CO) accumulation within the combustion chambers (furnaces) and are regulated by the norms 535 API (American Petroleum Institute) [16].

It was supposed simultaneously with gradual rejection of using the carbon-containing fuels to substitute the traditional energy sources: coal and hydrocarbons — particularly the natural gas (NG) — for hydrogen or for hydrogen — containing fuels, firstly — for the hydrogen mixtures with the natural gas (MG) [5–7].

For this purpose in Germany (for example) the Federal Ministry for Economic Affairs and Energy (BMWi) has decreed the statement regarding the future plans (till 2030–2050) on using the hydrogen as a fuel for industry, transport and energy supplying. It has been supposed accordingly mentioned document that the hydrogen of national and of import production [1] (especially from Ukraine) will provide the national (Germany) economics with CO₂-free fuel. Hydrogen will play a significant role in future, and till 2050 the fossil fuels (coal, oil, NG) would be excluded from the list of used fuels in Europe.

4. The system approach as the determinative criterion should be accepted as the suitable decision by consideration the complex: “thermal plant(s) (with account of combustion and heat recovery blocks) — energy supply process (with account of power balance — energy generation and consumption)” [18].

As usual in the present time, the solution of
the problem of decarbonization the environment is performed upon background of sustainability of the thermal technologies by different aspects: saving of raw materials, fuel(s) and energy, on the one hand, and provision of minimum CO2 emission by using the renewable energy sources and due replacement of the means of transport by electromobiles with concomitant reducing of harmful emissions [19].

The great deal of the results of energetics activity, providing the sustainable development of fuel energetics, concerns the thermal equipment of different branches of industry.

About 40 % of the energy, consumed in industry is used in industrial furnaces [19]. It’s a very important task — to ensure the advanced basic designs and the perfect operation technologies of proper effective fuel using plants (furnaces). The last demand is obligatory for fulfillment because the service life period of existent and perspective designs of the furnaces (reheating, melting, etc.) makes a lot of decades [19]. The aspect of CO2 avoiding by implementation the principles of sustainability, is mainly related to the heat treatment processes and furnaces. The proper approaches are relevant to the hardening shops [19] while from the standpoints of efficiency of fuel using (fuel saving) and accordingly requirement of prevention the environment pollution the most common solution consists in operations with combustion systems by means of option the most suitable burner designs and heat recovery facilities of the furnaces. Principle of the fuels’ diversity serves as a ground of an application of the biogases and gases from “power — to gas production” from the sustainable sources’ position [20].

Forming of fuel markets by nomenclature and structure

The specific peculiarity of forming the current markets of energy and fuel consists in periodic alternations of the priorities for control and manage with the proper systems from the economic, power, environmental and climate standpoints.

1. In the 60–70-th years of XX century the environmental (ecological) characteristics of power generation and consumption has become the determinative feature of the markets’ statement while from the beginning of XXI-th century the climate — influencing greenhouse emission, firstly — of C — containing compounds, has caused a warming of environment, at any rate — by opinion of some leading officials, public leaders and business managers [7]. Some aspects of CO2 formation by burning of different fuels, its greenhouse impact and atmospheric dissipation have been studied in our papers [5–7] along with analysis of air pollution.

An activity of the scientists and the experts in combustion area last time has been connected with an option the proper types of fuels and have been related to technologies’ development, providing minimization of C-containing compounds. The main attention has been paid to the CO2 influence upon the heat and mass exchange processes over the Earth’s surface [7].

2. Political activity of the world and EU organizations has promoted the tendencies of option and change the fuel and energy markets, directed for decarbonization of environment and thus preventing a warming of environment [2, 5, 7, 8]. At the UNO (United Nations Organization) Summit 2015, September (New York), the resolution on climate protection has been adopted for the first time in the international laws’ history [8]. An EU-wide emission trading scheme has been established for industry, energy and EU aviation (ETS system) to achieve 43 % reducing of greenhouse gases emissions compared to 2005 [2].

Main gas fuels at European markets

1. In connection with the serious alterations of environmental situation during the recent years, the diversification of the gas fuel market in Europe has happened. The resulting expansion of the range of values of the main combustion properies (laminar burning velocity \( S_L \), burning limits, flame stability and detonation indicators, ignition delay period, methane numbers) — on the one hand, and heat engineering characteristics (heat of combustion: higher, lower; corresponding Wobbe numbers), on the other hand, provides correspondence with new fuel’s properties [1, 20–23]. Finally, the natural conclusion — on influence of mentioned characteristics upon further prospects of the gas fuels’ use from the energy and environmental positions, including the climate impact — has been stated. The special attention has been paid to electricity production and upon the environmental restrictions being associated with the formation of CO2 [16] in frame of the problems
of attraction the “green energy” and “green hydrogen” [1–3]. Available hydrogen content, strongly limited at the initial stages of applied using the H₂, is among the factors, affecting the characteristics of the fuel if meets insignificant hydrogen content (9–15 % vol.) in the gas [20, 24].

2. In addition to the rich (high-calorie) fuels, such as LNG (liquefied gas — see below), various types of natural gas and biomethane do not cause complications when used in the majority of European countries. However, in contrast to the inclusion of H₂ and biofuels (like CH₄), produced with the help of electricity excess, obtained with the help of renewable energy sources — based components [24], the biomethane, produced of contaminated raw materials, may cause the appearance of some unwanted by-products. From the given circumstances’ standpoint, the natural gas can be considered as the most suitable basic compound of all fossil fuels (from the point of view of using the climate protection fuels) [24].

The European Union Directive RED (Renewable Energy Directive) 2009/28/EC has established the minimum quantitative indicators for using the following forms as the restrictive standard shares to 2020: 10 % of renewable energy — in transport while 20 % of renewable energy — upon the whole for total energy consumption. Biofuel belongs to renewable energy sources [25].

It should be noted that according to the Eurostat classification, the biogases does not included in the “Gas” category, nor into the “Fuel” category, but are included in the “All other renewable energies” category [13].

There are indications in the presentation [21] on main components of biogases (BG): CH₄ and CO₂ while the following compositions of BG with these gases are mentioned by CH₄/CO₂ shares, % vol.: 50/50; 40/60.

3. Prof. Jean-Bernard Michel has presented the main technologies suitable for conversion some types of biomass into heat or/and power with proper advantages and shortcomings [26].

Types of conversion pathways in dependence on biomass’ kind: thermal, biological, physico-chemical. The following criteria has been proposed for evaluation the energy conversion technologies: availability, environmental impact, specific price, performance, profitability, environmental impact. The thermal technologies under consideration on heat and electricity transformation: combustion, gasification, pyrolysis, anaerobic digestion, cogeneration.

The pre-treatment technologies include different processes of the raw material’s preparation: drying, torrefaction, hydrothermal conversion, grinding, etc.

4. Let select the gas fuels presented at the European market, with the similar heat engineering characteristics. The following gases would be ranged within the proper list, in the set of chosen gases fuels would be included the natural gas (NG of type H gases: Russland, Nordsee, Danemark — accord-ingly Germany’s classification), liquefied (LNG) gases and the biogas (BG) with the compositions, close to NG (96 % CH₄). By analysis, the results of comparison with the correlations of the specific basic characteristics: “heat of combustion — Wobbe number and methane number”— the serious fluctuations of Wobbe number will be displayed, especially if the gases with a 10 % addition of H₂ would be included into the number of tested fuels to be considered [24]. Due to variety of compositions of the natural gases supplied to the European market, as well as because the use of gases from alternative sources such as biogas and the process (technological) gases (gases from “power-to-gas” scenarios [20] or the non-fossil fuel gases, recovered gases [13]), the nomenclature of gases by chemical composition and by combustion characteristics is highly distinctive. The consumer’s properties of certain fuels in the glass, ceramic, and metallurgical industries come into conflict with the properties dictated by technology, which is caused by the strong impact of even a small change of production parameters upon the product quality, upon the efficiency of fuel use and on the corresponding environmental consequences of manufacturing the final products [20].

The last paper demonstrates the properties of various types of NG, as well as of gases, artificial by composition and chosen for evaluation the proportionality principle of combustion heat and Wobbe numbers of proper gas fuels. It has been established that the maintenance of the same insignificant heat loads does not ensure the conservation of the most important local characteristics of thermal processes from the heat-technological and environmental points of view (flame burnout, profiles of heat fluxes, etc.) [20]. Mentioned statement is related to the case of using the different gases, including the fuels of compositions, similar in terms of main components, or in terms of fluctuations in the composition of fixed fuel.
Novel ways of supplying the natural gas, proper gas mixtures and liquefied fuels’ maritime transport

The nowadays period is determined by the significant expansion of the fuel nomenclature in the world, which has been complicated by the instability of fuel supply, especially in the Europe, over the last year. These processes are caused by the climatic influence of greenhouse emissions in view of environmental and atmospheric challenges. The negative problems are connected with the carbonization of the environment under the conditions of burning the carbon-rich fuels (fossil fuels), and, on the other hand, make the consequences of political and economic processes associated with a great reduction of natural gas supplying by means of the main pipeline transportation from Russia to Europe.

An introduction of renewable natural gas and combined hydrogen-enriched natural gas supplying systems are recommended and presumed. It means renewable natural gas (RNG) and hydrogen — enriched natural gas (HENG) integration systems — according information of GTI-ENERGY’s analysis and approach (Supporting integration of emerging fuels as a low-carbon transition strategy / Virtual workshop, USA, Des Plaines IL, March 2023).

Under the specified conditions, the problem of maritime supplying of liquid fuels is focused upon attendant infrastructure, firstly concerning the liquefied natural gas LNG and connected with using the floating storage and regasification units (FSRUs) [4]. Meanwhile, two floating LNG terminals are setting up in the Dutch port of Eemshaven. The floating storage and regasification units (FSRUs) would convert LNG into gas for onshore distribution, with LNG reportedly coming via carrier from the US [4].

Peculiarities of sea transport. An LNG carrier represents a tanker, specially, intended to transport liquefied natural gas. A feature of an LNG ship is connected with specific peculiarity that makes it different from other bulk cargo carriers. The mentioned crafts are supplied with the insulated, temperature-controlled tanks that ensure the gas is kept in a liquid state at temperature about (–162 °C).

Special attention is paid to the important problem of fuel supply by sea, which, in particular, is provided due novel solution the problem of fuel provision — by means of the transport the less calorific fuel — an ammonia NH₃ [27]. An alternative to carbon-rich fuels is tanker transportation of liquid fuels of various composition.

Advantages of LPG fuels (refinery gases) [27]:
— LPG have a high specific energy capacity;
— convenient form of storage;
— reliable distribution networks;
— lack of toxicity;
— reduced CO₂ emissions compared to traditional fuel;
— significant reduction of emission NOₓ (≈ 83%);
— practically no emission SOₓ, as well as of a solid particles in exhaust gases.

The Finnish company “Wärtsilä” is engaged with the problems provision of the research and use the ammonia as a fuel of the future [27] from various standpoints and issues. Among the problems to be solved, are:
— the production, storage, supply of high-quality fuels,
— various technological solutions,
— leading off the technology using of the dual-fuel engines,
— combining fuel supply systems and nodes, including with schemes for protection from emissions of ammonia and of dinitrogen oxide N₂O (the last one is a greenhouse gas with corresponding negative impact) [27].

Section 2. Thermodynamics of using fuels and comparative evaluation of gas fuels

1. Efficiency of fuel using as an impact-factor of reduction the carbon emission. To prevent the further environmental warming till the limit value of 1.5–2.0 °C before the control period of 2050, it has been foreseen to exclude using of fossil fuels to minimize emission of CO₂ as the principal greenhouse gas. Generally to the number of greenhouse compounds are related, besides CO₂, the following components: CO₂, CH₄, HFC, SF₆ and NF₃, in equivalence to CO₂ [8].

EU has corrected the climate purposes of reducing the greenhouse gases emission for 2030 in comparison to 1990 by 40 % [1, 2, 11].

Very interesting statement on need for account the correlations between efficiency of tested fuel’s use and expected CO₂ emission to atmosphere has been discussed in the paper [3] and review [8].

J. G. Wunning has indicated an opportunity of twice lowering an emission of CO₂ due enhancement of η, by value, distinctive for the combustion
plant [3]. For example by operation the reheating furnace at 1000 °C the CO₂ emission could be evaluated by specific value C_CO₂ = 0.45 kg CO₂/kWh of natural gas combustion’s energy in case of furnace operation without arrangement the heat recovery facilities. In case of operation the furnace, equipped with recuperative or regenerative burners the CO₂ issue will be reduced to C_CO₂ = 0.2–0.25 kg CO₂/kWh [3]. It means that in the last case an efficiency of fuels energy fuel using η_f was enhanced approximately double due arrangement the heat recovery system in addition to principal combustion system.

2. The energy demands from the thermodynamic foundation could be determined with accuracy of additive constant. It means that the absolute amount of energy is useless for application and couldn’t be measured in physical processes [28].

By this reason we will apply the specified alterations of energy — the general heat — in particular — absolute or relative values by means of energy changes: gains, losses or in form of variation of proper ther modynamic functions — see below.

A. In our case with account of need to operate with a heat Q value, the total (chemical) enthalpy I serves as a characteristic of energy under isobaric performing of the combustion process (p = const; dp = 0). We’ll use the elementary enthalpy change as a measure of gain the energy or heat. In accordance with the first origin of thermodynamics [29–31]:

\[ dq = du + pdv + vdp = du + pdv = di. \] (1)

By this should be taken into account that the functions: work A and heat q with the increments δA and δq — correspondingly (in form of differentials) — are depending on the way of reaching the final state of the system — while each of functions: the internal energy u and enthalpy i — respectively — don’t depend on the way of the system’s transformation. An equation of the first origin of thermodynamics [29, 30] for the isobaric combustion process could be presented in differential form by using the notions of complete (di) and incomplete δq differentials:

\[ di = δq, \] (2)

that means an opportunity of operation with the total enthalpy of combustion products as the rep resentative energy characteristic of working medium (body).

B. In accordance with the Carnot’s theorem [32], the reversible idealized heat engines have the maximum efficiency, determined by equation [28, 30]:

\[
\eta = 1 - \frac{Q_2}{Q_1} = 1 - \frac{T_2}{T_1},
\] (3)

where \( T_1 \) and \( T_2 \) — an absolute temperatures, K, inside of hot and cold reservoirs, \( Q_1 \) is a heat amount or heat flux, absorbed from hot reservoir of temperature \( T_1 \) and \( Q_2 \) — heat flux, transferred to the cold reservoir of characteristic temperature \( T_2 \). In accordance with above proven statement (see equation (2)) the increment of total enthalpy \( ΔI \) could be considered instead of \( Q \).

Role of the outward medium is established by the 2nd origin of thermodynamics for non-ideal systems [28, 33].

C. Basing upon given above statement, relevant to requirements of heat (energy) calculations and presentation, an amount of heat \( Q \) or value of heat flux(es) could be computed with calculations through the difference of two proper values (by location or conditions of definition): the total enthalpies of individual substances \( I_X(T_X) \) — with proper parameters — or the mixture of combustion products \( I_{CP}(T_{CP}) \):

\[
Q = I_{X,1} - I_{X,2}; Q_{CP} = I_{CP,1} - I_{CP,2}.
\] (4)

We are passing to procedures with the excessive values of the enthalpies in form of enthalpies’ difference of the parameters’ values at current temperatures \( T_X, T_g \) by the standard temperature \( T_0 \).

For any component \( X \) and for the mixture of combustion products \( (q, CP) \) we have the following determinations for excessive values of the characteristic:

\[
ΔI_X = I_X - I_{X,0}; ΔI_g = I_g - I_{g,0} = I_{CP} - I_{CP,0}.
\] (4a)

The calculation equation for efficiency of using the energy within combustion system could be kept with transformation the equation (1) into integral form and by using an analogy with equation (3).

D. There are number of the fuels’ characteristics, defined with the help of the values of total enthalpy or excessive total enthalpy:

\[
\eta = 1 - \frac{ΔI_{f,min}}{ΔI_{f,max}} = 1 - \frac{ΔI_{g,min}}{ΔI_{g,max}} = 1 - \frac{T_{min}}{T_{max}},
\] (5)
where the excessive enthalpies \( \Delta I_{g,ex} \approx \Delta I_{g,min} \) and \( \Delta I_{g,max} \approx \Delta I_{g,T} \) meet correspondingly the minimum (exit) and maximum (theoretical, adiabatic) \( T_T \) temperatures.

3. Mentioned values of specific \( \text{CO}_2 \) could be evaluated qualitatively with an account of efficiencies: of fuel use \( \eta_f \) and of power plant’s (furnace’s) processing \( \eta_{fu} \). Specific effluents are calculated by means of application the Carnot’s equation \([28, 32]\) while our transformation due transfer to using the excessive total enthalpies could be presented in form:

\[
\eta_f = 1 - \Delta I_{f,ex}/\Delta I_{f,T};
\]

\[
C_{CO2} \sim \eta_f^{-1}, \tag{7}
\]

while efficiency of the fuel using system on the whole \( \eta_{fu} \):

\[
\eta_{fu} = \eta_{f,ex,ch} = \eta_f, \tag{8}
\]

where \( \Delta I_{f,T} \) — excessive total enthalpy of combustion products of 1 kg of fuel by theoretical combustion temperature \( T_T \) of CP for the fuel-oxidant mixture under consideration; \( \Delta I_{f,ex} \) — excessive total enthalpy of flue gases (combustion products CP) at the exit of combustion chamber (lower subscript “f,ex,ch”) or at the exit of flue gases pathway the lower subscript symbol “f,ex,out” (for the issue of waste combustion gases). It means that efficiency of the plant furnace could be established by equation:

\[
\eta_{fu} = \eta_{f,ex,ch} = \eta_f, \tag{8}
\]

where efficiency of the fuel using system on the whole \( \eta_{fu} \):

\[
\eta_{fu} = \eta_{f,ex,out} = 1 - \Delta I_{f,ex,out}/\Delta I_{f,T}. \tag{9}
\]

Mentioned efficiencies could be introduced and used in accordance with the notions of partial and general efficiencies of the system \([29]\).

4. Calculation of thermal (heat, power) characteristics of the gas fuels with using the total enthalpies.

Consideration of the problem of using the fuel and energy with evaluation the efficiency. “Thermal plant — heat recovery appliance(s)” should be foreseen for consideration the proper installation for analysis.

The last condition means, as a rule, an enhancement of an air-oxidant preheating: \( T_a > T_0 \); and theoretical combustion temperature \( T_T (T_a > T_0) \) will exceed \( T_T \) under standard conditions, where \( T_a = T_0 \).

Accordingly Carnot’s theorem and efficiency of Carnot’s cycle (equations (3)) by supplying the firing system with recuperative heat exchanger:

\[
\eta_f (T_a > T_0) > \eta_f (T_a = T_0). \tag{10}
\]

By all cases of considered bio-fuels’ utilization under the NG replacement, the alternative fuels consumption \( B_f \) must be increased not only because of its lower combustion heat compared with NG.

In Fig. 1 the efficiencies \( \eta_f \), \( \eta_H \), \( \eta_{eff} \) of fuel utilization and of operation the power or process plants are presented to compare the power characteristics of NG and alternative fuels (AF). It has been stated that the more is \( T_T \) for the tested fuel type, the higher is efficiency \( \eta_f \) fuel using under the conditions of supporting the same operation (lower) temperature \( T_{ex} \).

Exergy efficiency \( \eta_{eff} \) is higher by value than \( \eta_H \) for the case supporting the operation temperature.
of the process or plant. By this our conclusion follows of statement by G. Hammond that “the overall exergy efficiency of industrial sector is much lower than corresponding energy efficiency” [34, 35]. The reason of mentioned discrepancy is explained by different objects and proper notion the concepts of the compared efficiencies accordingly our approach and by of English source [35].

Firstly, it should be remember that value of serviceability (and entropy) of any system is less than enthalpy as an available energy and, on the contrary, the enthalpy is higher by value than entropy [18].

Secondly — our approach concerns the thermodynamically ideal systems. The total analysis has been performed under “ideal furnace” approximation (the system without power losses) regarding local efficiency under specific temperature.

Efficiency calculations are performing by excessive values of main power (energy) characteristics for combustion products CP (flue gases): subscript “g” — for 1 kg of CP, subscript “f” — for CP of 1 kg of fuel.

Range of $T_g$ variation as the working medium (body) for the fuel utilization plant’s (furnace, boiler, engine) analysis: $T_T > T_{f} > T_{ex}$. In this case the common subscript “g” is replaced by “f” (current value) and “ex” (at the plant’s exit).

**Next types of efficiency characteristics could be proposed:**
- $a$ — of fuel utilization
  $$\eta_f = \frac{\Delta E_{f, T}}{\Delta I_{f, T}}$$  \hspace{1cm} (11)

  (* — for CP of stoichiometric ($A = 1.0$) fuel-air ($[O_2] = 20.95 \%$ ) mixture; $T_o = 298$ K.);
- $b$ — of heat (energy) utilization
  $$\eta_h = 1 - \frac{\Delta I_{f, ex}}{\Delta I_{f, T}}$$  \hspace{1cm} (12)

  In case of stoichiometric combustion, by $T_{ax} = T_a = 298$ K and an air-oxidant application $\eta_h = \eta_f$;
- $c$ — of change the serviceability of system under consideration
  $$\Delta E_g(T) = E_{g}(T) - E_{g}(T_0) = \Delta I_g - T_0 \Delta S_g;$$  \hspace{1cm} (13)

  $$\Delta E_{g, T} = E_{g}(T_T) - E_{g}(T_0) =$$

  $$= \Delta I_{g, T} - T_0 (S_{g, T} - S_{g, 0}).$$  \hspace{1cm} (14)

  In principle, the similar approach has been used later by C. Dyer and G. Hammond, who didn’t use the “total enthalpy” concept but took into account the change of chemical potential of separate components of the working medium by the analysis of the combustion process. The proper procedures has been simplified in [35].

Taking into account our methodology on calculation the exergy efficiency [18], the following equation was used:

$$\eta_{eff} = 1 - \frac{\Delta E_{f, ex}}{\Delta E_{f, T}} = 1 - \frac{\Delta I_{f, ex} - T_0 \int_{T_0}^{T_T} T^{-1} dI_{f, g}}{\Delta I_{f, T} - T_0 \int_{T_0}^{T_T} T^{-1} dI_{f, g}}. \hspace{1cm} (15)$$

Efficiency types $a$ and $b$ are related to enthalpy efficiency, $\eta_{eff}$ — to exergy one.

As it’s known, two various constituents of the exergy: physical and chemical — are included in total exergy value. If the process of combustion or gasification is under consideration than chemical exergy is taking into account. In case of efficiency analysis of fuel utilization plant, the energy transformation of equilibrium combustion products’ state, beginning of $T_T$ till $T_{ex}$, is computed. Thus, the $\Delta E$ value is mainly of physical nature with less significant chemical energy input.

The data in Fig. 1 demonstrate an influence of the flue gases’ temperature $T_{f}$ at the exit of flue pathway on efficiency of fuel using of two types: heat (enthalpian) $\eta_h$ for plant and exergy $\eta_{eff}$ by combustion of different gas-air mixtures.

Below are considered in comparison the tendencies of change the enthalpy and exergy efficiencies of fuel using $\eta_f$ and $\eta_{eff}$ by means evaluation the 1st and 2nd derivatives by modulus and with account of the sign: (+) or (−).

**The contrary trends could be observed by consideration** the final results. Comparing the efficiency of use the available combustion heat of processes with account of fuel potential ($\eta_{eff}$) and efficiency of fuel using itself, by analogy with evaluation accordingly Carnot’s equation ($\eta_{eff} = \eta_h$) the following statement could be established:

- within the range of low CP temperatures $T_0 < T_g < 800$ K

\[
\begin{align*}
\frac{\partial \eta_f}{\partial T_g} & > \frac{\partial \eta_{eff}}{\partial T_g} \\
\frac{\partial^2 \eta_f}{\partial T^2} & > \frac{\partial^2 \eta_{eff}}{\partial T^2}
\end{align*}
\]  \hspace{1cm} (16)
— within the range of low CP temperatures $1800 < T_g < T_T$

\[
\begin{align*}
\frac{\partial \eta_f}{\partial T_g} &< \frac{\partial \eta_{\text{eff}}}{\partial T_g} \quad ; \\
\frac{\partial^2 \eta_f}{\partial T_g^2} &< \frac{\partial^2 \eta_{\text{eff}}}{\partial T_g^2} \\
\frac{\partial \eta_f}{\partial T_g} &> \frac{\partial \eta_{\text{eff}}}{\partial T_g} \quad ; \\
\frac{\partial^2 \eta_f}{\partial T_g^2} &> \frac{\partial^2 \eta_{\text{eff}}}{\partial T_g^2}. 
\end{align*}
\]

From the given thermodynamic analysis’ generalization in form of inequalities, could be seen that within the range of comparatively low operation temperatures the serviceability of the fuel using is more stable (conservative) characteristic than direct fuel using efficiency: exergy efficiency $\eta_{\text{eff}}$ exceeds the values of enthalpian efficiencies:

\[
\begin{align*}
\eta_{\text{eff}} > \eta_H; \\
\frac{\partial \eta_{\text{eff}}}{\partial T_g} &\to 0 \\
\text{under } T_g &\to T_0.
\end{align*}
\]

Within the range of high operation temperatures more sharp change of $\eta_{\text{eff}}$ values by alteration the operation temperatures takes place under ensuring the attendant consequence under supporting the same CP temperatures:

\[
\eta_{\text{eff}}(T_{CP}) > \eta(T_{CP}).
\]

**Principal characteristics of the gas fuels.**

**Methods and technique of calculation the basic data**

1. **The firing and heat (power) character-**

istics of the fuels serve as the basic data for selection the suitable energy sources with account the nowadays demands from the climate and environmental standpoints.

Taking into account the situation with the demands to the perspective fuels under conditions of sustainability and decarbonization of environment, the methane-hydrogen mixtures (mixed gases MG) could be chosen as the most suitable type of fuel for the future using. The MG gases are considered and taken with the characteristics, appropriate for the next selection, studying and the fuel’s data generalization.

It should be stated that the technique, providing an enhanced efficiency of fuel using, continues to present the greatest request for the further engineering activity, development the technologies and adjustment the proper type of fuel, at any rate — in the branch of industry with a great number of low-effective plants.

In case of the system with the water vapor as the working medium (body) or when using its fraction, an assembly could be foreseen to combine the system due introducing the evaporation/condensation processes and increasing the complete efficiency of the plant, equipped with mentioned assembly. The proper approach has been advanced for different equipment, beginning of furnaces and boilers and including the combustion systems of turbines [36]. The modern systems of indicated type are presented with the power plants equipped with the water vapor pump system or using the Maisotsenko-cycle [37]. This direction will be studied and discussed in the 2nd part of present work.

**The principal thermal (heat) engineering characteristics (combustion heats and Wobbe numbers)** of perspective fuels, intended to substitute the fossil fuels for decarbonizing fuel gases (methane-hydrogen mixtures) have been computed with the help of original code basing upon fundamental energy functions — total enthalpies of individual components (see below) and the proper values for the gas mixtures. The Wobbe numbers give an opportunity to compare the heat energy for the plants supplied with different fuels in conditions of supporting the fuel’s pressure of fixed value with account of invariable density of combustion air ($\rho_a = \text{const}$):

\[
W_{of} = Q_f \left( \rho_f \rho_f^{-1} \right)^{0.5};
\]

\[
Q_{f,use} \sim (\Delta P_f \rho_f^{-1})^{0.5},
\]
where $\rho_f, \rho_a$ — the density of fuel and combustion air — correspondingly.

The Wobbe numbers: higher $W_{oh}$ and lower $W_{ol}$ — meet the combustion heats: higher $Q_h$ and lower $Q_l$ — for the fuel under consideration. In Fig. 2 are presented the heat of combustion: higher $Q_h$ and lower $Q_l$ per unit of mass (1 kg) and volume (1 nm$^3$), that is, for objective — normal conditions ($0^\circ$C), despite the fact, that the determination of heats of reaction and, accordingly, heats of combustion as such — are universal energy characteristics performed for standard conditions ($25^\circ$C = 298 K). Numerical values $Q_h, Q_l$ (Fig. 2) and Wobbe numbers $W_{oh}, W_{ol}$ (Fig. 3) for 1 kg and 1 nm$^3$ of fuel mixture are additionally given in the Table 1 as well as the theoretical combustion temperature values $T_T$.

2. Combustion heat value is the first representative characteristic of any fuel, determining both the demand for fuel by consumption required flow rate and efficiency of specific fuel using in the plant.

To compute the combustion heat value of fuel, the proper total enthalpies are engaged. In accordance with the definitions for the determinations under standard conditions ($p_0, T_0$):

$$(1+\Omega_{st})^{-1}Q_f = I_{CP,T} - I_{CP,0} = I_{in,0} - I_{CP,0},$$

where $I_{CP,T}, I_{CP,0}$ — the specific total enthalpies of mass unit (1 kg) of initial fuel-oxidant mixture and that for combustion products — respectively — at standard conditions while $I_{CP,T}$ — specific enthalpy of CP at theoretical combustion temperature.

As to combustion heat values LHV and HHV, it’s necessary to underline and understand that these notions and proper values are conditional (for industrial users). By real circumstance the requirements couldn’t be executed because both heats (LHV, HHV) don’t exist as the physical parameters. It could be explained by following basic circumstances.

In accordance with the statement on thermodynamic equilibrium, the composition of separate components within the mixture of CP meets proper approach. Under calculations the $H_2O$ component represents the two-phase system if the temperatu-
Table 1. Energy and firing engineering — characteristics of mixed methane-hydrogen fuel, including technical theoretical (adiabatic) combustion temperatures $T_r$, depending on the share of hydrogen in gas fuel, % vol., under standard initial conditions (temperature $T_0 = 298.15$ K, pressure $p_0 = 0.101325$ MPa)

<table>
<thead>
<tr>
<th>H₂, % vol.</th>
<th>CH₄, % vol.</th>
<th>$T_r$, K</th>
<th>$Q_f$, MJ/kg</th>
<th>$Q_h$, MJ/kg</th>
<th>$Q_l$, MJ/nm³</th>
<th>$Q_h$, MJ/nm³</th>
<th>W₀, MJ/nm³</th>
<th>W₀, MJ/nm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>2228</td>
<td>50.03</td>
<td>55.51</td>
<td>35.81</td>
<td>39.84</td>
<td>44.08</td>
<td>48.92</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
<td>2232</td>
<td>50.99</td>
<td>56.70</td>
<td>33.31</td>
<td>37.13</td>
<td>42.92</td>
<td>47.73</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>2238</td>
<td>52.16</td>
<td>58.14</td>
<td>30.81</td>
<td>34.43</td>
<td>41.75</td>
<td>46.54</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
<td>2244</td>
<td>53.60</td>
<td>59.92</td>
<td>28.30</td>
<td>31.72</td>
<td>40.57</td>
<td>45.35</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>2251</td>
<td>54.53</td>
<td>62.18</td>
<td>25.80</td>
<td>29.02</td>
<td>39.39</td>
<td>44.18</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>2261</td>
<td>57.83</td>
<td>65.14</td>
<td>23.27</td>
<td>26.31</td>
<td>38.23</td>
<td>43.06</td>
</tr>
<tr>
<td>60</td>
<td>40</td>
<td>2272</td>
<td>61.12</td>
<td>69.19</td>
<td>20.79</td>
<td>23.61</td>
<td>37.13</td>
<td>42.04</td>
</tr>
<tr>
<td>70</td>
<td>30</td>
<td>2287</td>
<td>65.88</td>
<td>75.07</td>
<td>18.29</td>
<td>20.90</td>
<td>36.16</td>
<td>41.20</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>2308</td>
<td>73.42</td>
<td>84.37</td>
<td>15.79</td>
<td>18.20</td>
<td>35.47</td>
<td>40.76</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>2337</td>
<td>87.14</td>
<td>101.30</td>
<td>13.28</td>
<td>15.49</td>
<td>35.45</td>
<td>41.21</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>2383</td>
<td>119.96</td>
<td>141.79</td>
<td>10.78</td>
<td>12.79</td>
<td>37.47</td>
<td>44.29</td>
</tr>
</tbody>
</table>

res of CP is below saturation temperature or dew point. At the same time only one-phase state for $\text{H}_2\text{O}$ is foreseen by calculations the combustion heat. By this reason the principal incompatibility the conditions of calculation the combustion process with the formal requirements for definition the LHV value (H₂O of CP — only in form of water vapor) and HHV (H₂O — only in condensed phase — the liquid phase (water)) is observed.

The rated (computation) dependences have been composed for calculation the LHV and HHV regarding the studied and tested fuels. The following formulas are used in frame of our statement and methodology for the cases of calculation the LHV, HHV of the fuels, containing hydrogen in own composition of the fuels, particularly including any hydrogen fraction (share):

\[
Q_{f,l} = (1 + \Omega_{st}) (I_{in,0} - I_{CP,0})^{(WV)};
\]

\[
Q_{f,h} = (1 + \Omega_{st}) (I_{in,0} - I_{CP,0})^{(W,cond)};
\]

where $I_{CP,0}^{(WV)}, I_{CP,0}^{(W,cond)}$ — correspondingly: the total enthalpy of unit of combustion products at standard conditions with $\text{H}_2\text{O}$ in form of water vapor “WV” (the first) or in form of water, liquid “W” (the second) — correspondingly.

Another group of characteristics compose the firing properties of fuels. The methane number MN is one of the representative firing properties, its value gives the opportunity to compare the detonative ability of the tested fuel in relation to the methane-hydrogen mixtures.

In Fig. 4 are presented the methane numbers of some the most widespread types of fuels. The fuel’s MN for the methane makes MN (CH₄) = 100 while for the hydrogen MN (H₂) = 0. The last equation means that ability to resist detonation for hydrogen makes zero (is absent). For alkanes CₙH₂ₙ₊₂ the MN value is decreased with increasing of $n$ value: MN $\rightarrow$ 0 under $n \rightarrow$ 4–6 and more.

The MN of fuel X is equal to the methane content (% vol.) in the CH₄-H₂ mixture of composition, providing the same detonation activity (explosive limits, detonation velocity [17]) as the tested gas fuel:

\[
\text{MN (X)} = \text{MN (CH₄/H₂)} = \frac{D_{v,CH₄}(CH₄/H₂)}{D_{v,CH₄}},
\]

where $D_{v,CH₄}$ — the volume share of CH₄ in the fuel mixture (in this case — CH₄ with the hydrogen), % vol.

On the contrary to methane number (MN), for motor octane testing (MON) the upper critical values for CH₄ exceeds 100 [38].

The MN values for some widespread modern fuels, presented in Fig. 4, b, is have been correlated with the MON values [38].

Historically, an evaluation of detonative properties of the fuels has been initiated with gasoline as a fuel. The initial researches were relevant to the sparkignited internal combustion engines and were performed more than 80 years ago [38].
Figure 4. Methane numbers MN for fossil and an alternative gas fuels by the testing results with using different techniques: a — MN in dependence on content of [CH₄] and [H₂], % vol., in the control fuel (triangular sketch); b — by the results of empirik "knock rating technique" testing [38] for 8 fuels of different composition.

The knock phenomena is the most suitable property for the fuels evaluation. Motor Octane Number (MON) is the proper feature by knock testing the LPG but numerical estimation the mentioned characteristic has required the statement of correlation between MON and MN values

\[
\text{MN} = 1.445 \text{ MON} - 103.42; \quad (27)
\]

\[
\text{MON} = 0.679 \text{ MN} + 72.3. \quad (28)
\]

Using the double approach to estimation the features of the fuel under consideration gives the opportunity for accurate prediction the fuel’s properties.

**Brief content and conclusion**

1. The most actual trends taken into account by option the fuels and by forming the modern fuel supplying markets, are the following directions:
   - substitution the fossil fuels for alternative ones, particularly — with bio-fuels;
   - using the carbonless fuels for preventing an emission of the greenhouse gases and warming of environment;
   - substitution the natural gas with hydrogen and mixed gases (methane-hydrogen mixtures, ammonia and the mixtures NH₃ + CH₄ , NH₃ + H₂);
   - substitution of gas pipeline supplying the natural gas for supplying the LNG (liquefied natural gas) to the consumers, located at the great distance from the fuel sources within the whole coastal territories, and the Central European countries.

   The floating storage and regasification units (FSRUs) would convert LNG into gas for onshore distribution.

2. Some new trends directed to envisage an activity in supplying the fuels at European and world markets are presented and analyzed: the maritime tanker transport of liquefied gas fuels (LNG, LPG), particularly concerning the natural gas (CH₄), and relevant to ammonia (NH₃).

   Two newly advancing systems of fuels supplying have been presented and analyzed:
   - the interconnect for Emerging Fuels into Energy Delivery Networks — Introducing of renewable natural gas (RNG) and hydrogen-enriched natural gas (HENG) integration including incorporation into the natural gas pipeline (GTI-Energy, USA);
   - the great expansion of maritime tanker transportation of liquefied gas fuels: LNG, LPG. The last time the sea transport of ammonia NH₃ is practiced on a definite scale (the Finish company “Waertsiila”).

3. Special place by forming the markets with option the preferable types of fuels and the processes (technologies) of the fuels application takes the problem of enhancement an efficiency of fuel utilization mainly due intensification the technological and heat and mass exchange processes. The last are realized in the proper designs of com-
bustion chambers supplied with improved heat recovery systems.

Really, fuel using efficiency \( \eta_f \) is highly influencing factor, determining the environmental and climate characteristics of combustion processes. By this reason roughly 0.45 kg CO₂/kW·h is emitted to the atmosphere by power plant operation with a cold air — oxidant while by fuel burning process at the same temperature conditions (1000 °C) in the reheating furnace with preheated air-oxidant provides emission of 0.2–0.25 kg CO₂/kW·h.

4. The most advanced power engineering and reheating combustion systems are related to the processes of “wet combustion” in combination with the heat recovery facilities: two-staged recuperative system provides a simultaneous preheating of the initial burning components (mainly — combustion air) with its humidification. To the mentioned recuperative system is related the water vapor pump systems and the heat and mass exchange units realizing M-cycle (Maisotsenko cycle). The proper plants are providing enhancement of efficiency of the plant on the whole by means of control with the low-temperature section of circuit.

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Nomenclature

- \( C \) — concentration of component
- \( D \) — fraction of component
- \( E \) — exergy
- \( I \) — total enthalpy
- \( i \) — enthalpy as a thermodynamic function
- \( P \) — static pressure
- \( Q \) — amount of heat, heat flux, reaction’s heat value, combustion value
- \( q \) — heat as a thermodynamic function
- \( m \) — mass amount
- \( S \) — entropy
- \( T \) — temperature
- \( u \) — internal energy (thermodynamic function)
- \( v \) — specific volume of the working medium (body)
- \( X \) — component X
- \( \eta \) — efficiency of using fuel or energy
- \( \lambda \) — air excess factor
- \( \Omega \) — mass ratio “oxidant : fuel”
- \( \rho \) — specific density of working medium (body)

Subscript’s indices

- \( a \) — combustion air
- \( CP \) — combustion products
- \( eff \) — efficient (for exergy)
- \( eq \) — equilibrium
- \( ex \) — at the exit of the combustion chamber
- \( fl \) — at the exit of the products’ pathway
- \( f \) — fuel
- \( g \) — for fully burnt combustion products
- \( H \) — higher value
- \( ln \) — for initial components and conditions of combustion
- \( l \) — lower value, for laminar combustion velocity
- \( T \) — for theoretical combustion temperature
- \( use \) — for useful energy
- \( X \) — for component X
- \( \Sigma \) — for total values
- \( 0 \) — by standard conditions (\( P_0 = 0.101325 \) MPa, \( T_0 = 298 \) K)

Abbreviation

- API — American Petroleum Institute
- BG — biogas
BMWi  
Ministry for Economic Affairs and Energy, Germany

CCS  
carbon capture and store process

CP  
combustion products

DRI  
direct reduction iron

EC  
European commission

EU  
European Union

FSRU  
Floating storage and regasification unit

GTI ENERGY  
Gas Technology Institute, USA

HENG  
hydrogen enriched natural gas

LNG  
liquefied natural gas

LPG  
liquefied petroleum gas

MN  
Methane number

MON  
motor octane number

NG  
natural gas of types (European groups) H and L

RNG  
renewable natural gas

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Received April 5, 2023
Кліматичні та екологічні засади використання палива, що впливають на зміну тенденцій газопостачання в Європі та Україні.
Частина 1. Сучасні вимоги до вибору газових палив.
Термодинамічна оцінка основних характеристик газового палива

Розглянуто вихідні положення формування паливних ринків Європи в рамках концепції сталого розвитку економіки країн з урахуванням основних обмежень, перш за все, впливаючих на кліматичні та екологічні наслідки використання палив. Зазначений підхід зумовив у минулі роки одночасне збільшення абсолютних обсягів споживання мінеральних (органічних, вуглевмісних) палив та скорочення їхньої долі в загальному паливному балансі. Відповідні зміни відбулися за рахунок виробництва та споживання альтернативних, у тому числі відновлюваних палив та джерел енергії.
Проаналізовано нові схеми, способи та шляхи постачання палив, включаючи морські перевезення здійсненням палив (здріженого природного газу LNG, рідких вуглеводнів LPG, аміаку NH₃), створення відповідного танкерного флоту з плавучими та наземними системами ретрансляції та зберігання (схову) газу (FSRU), а також системи, що забезпечують об'єднання трубопровідів при паливопостачанні, в тому числі збагаченого воднем природного газу (HENG).
Згідно з культивованими поглядами, глобальне потепління розглядається як наслідок карбонізації атмосфери у зв'язку з викладами С-вмісних продуктів згорання (CO₂) в атмосферу. Зазначений внесок CO₂ в забруднення атмосфери викликаний недостатньою ефективністю використання палива, а чисельні значення наведено на прикладі нагрівальних печей (в печах спалається до 40 % загального обсягу споживання палива промисловість). Якщо рівень викидів звичайної системи спалювання природного газу в печах пов'язано з рівнем викидів до 0,45 кг CO₂/кВтгод, то у випадку оснащення печі ефективною системою утилізації теплоти викидних газів забезпечується скорочення викидів до 0,2–0,25 кг CO₂/кВтгод (Wunning, J.).
З огляду на визначальну роль ефективності використання палива ηₚ у масштабах забруднення атмосфери викидами парникових газів (CO₂) виконано термодинамічний аналіз енергоефективності з оцінкою ентальпійних ηₑ та ексегетичних ηₑₑ ККД систем спалювання. Здійснено порівняльні розрахунки ККД для випадків використання різних газових палив у діапазоні температур від стандартної T₀ до теоретичної температури горіння Tₜ. З використанням положень ріноважної термодинаміки за оригінальними авторськими методиками виконано розрахунки теплоенергетичних характеристик палив: вищої Qₑ та нижчої Qᵣ теплоти згорання, вищої W₀ₑ та нижчого W₀ᵣ чисел Воббе, теоретичної (адіабатної) температури горіння. Визначено вплив вмісту водної в сумішах CH₄–H₂ газових палив на згадані властивості.
З урахуванням наведених вогнетехнічних характеристик розглянуто формування метанового числа MN органічних та альтернативних палив. Співставлено накопичені чисельні значення MN для найбільш поширенних типів палив. Бібл. 38, рис. 4, табл. 1.
Ключевые слова: виодновлева енергія, водень, декарбонізація, ККД паливовикористання, метанове число МН, паливний ринок, повна енталпія, вища та нижча теплота згоряння, термодинамічний аналіз, утилізація теплоти.

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