Journal of International Scientific Publications:
Materials, Methods & Technologies, Volume 7, Part 1
ISSN 1313-2539, Published at: http://www.scientific-publications.net

MODERN APPROACH TO THE PROBLEM OF FOSSIL GAS FUELS REPLACEMENT BY ALTERNATIVE FUELS

Boris Soroka[1]
Gas Institute, National Academy of Sciences, Kiev, Ukraine

Abstract

New scientific and engineering fundamentals of fuels substitution have been developed instead of obsolete methodology "Interchangeability of Fuel Gases" developed in USA and existing from the middle of XXth century. To perform the complex prediction of total or partial substitution of given flow rate of natural gas NG for alternative gases AG the following parameters are to be predicted: plant utilization efficiencies – regarding fuel and energy utilization, the last in form of heat η_H and exergy η_{eff} efficiencies, saving or overexpenditure of the NG flow rate in the gas mixture with AG, specific fuel consumption b_f and specific issue of harmful substances C_t – pollutants in the combustion products (C_{NOx}) and greenhouse gases (C_{CO2}).

Certification of alternative gas fuels and fuel mixtures as a commodity products is carried out in frame of our approach with necessary set of characteristics, similar to those accepted in the world practice.

Key words: *alternative fuel, fuel replacement (substitution), natural gas, process gases, theoretical combustion temperature, thermodynamic equilibrium computations, total enthalpy.*

INTRODUCTION

The trends and situation in area of fuels utilization as primary energy sources is distinguished by continuous change – by countries and from year to year. New energy sources are arisen due to prove and opening the new deposits of fossil fuels and gas fields as well as by means of implementation the processes of using the non traditional fuels. At any rate bigger half of primary energy demands are provided at the expense of hydrocarbons (of order 60 % – see below) both of natural or casing – head gases and by crude oil.

Last time period is characterized by essential widening list of the fuels types been used in industry, residential and district heating systems, engines etc (Soroka, 2010; Ptasinski *et al*., 2006; Houa *et al.*, 2011). This situation is caused by deficiency and increasing cost of hydrocarbon fuels all over the world (excepting USA (Liss, 2012) and by attempt to substitute natural gas for alternative gas fuels (AGF). The same is related to the types of the appropriate oxidants. Along with serious spreading of oxy – fuel processes particularly in metallurgy (Vestenberg *et al.*, 2007), application of humidified or/and of oxygen depleted oxidants (air) took a new impulse because of environmental reason or accounting needs of cogeneration systems (Fossum and Beyer, 1998; John, 2002). An air of lower O_2 content is using as an oxidant when combustion system of thermal plant is supplied with lean flue gases from other cogeneration units instead of normal combustion air. That's why creation of modern scientific and engineering foundation of fuels replacement is of paramount importance (Soroka (HiTACG), 2010).

[1]Address all correspondence to boris.soroka@gmail.com

1. STATE-OF-THE-ART / PRESENT APPROACHES TO ACCOUNT TYPE OF FUEL

The problem of replacement of the combustible of any composition and caloricity by other fuel gas ("Interchangeability of Fuel Gases") (Weber, 1996) has appeared some decades ago in connection with season change the need for gas flow rates. The problem is actual when the combustible composition is changed while the gas equipment been installed (the burners) is kept.

An existing methodology of fuel substitution in case of its composition change and if the fuel type is varied (mentioned "Interchangeability of Fuel Gases") was developed in the second half of XX-th century mainly from the combustion stability standpoint and from the demands for the flame characteristics supporting, firstly for the conditions of utilization the domestic fuels and appropriate appliances.

It's understandable that for these cases the simplest burners are used without any special auxiliary facilities for control the flame characteristics and for provision of burning stability. As a consequence the criteria of supporting the stable flame and the for combustion completeness have been assumed as the principal requirements. American Gas Association (AGA) has selected the following characteristics (Weber, 1966):

- lifting index I_L (for guaranteeing the upper load limit);
- flashback index I_F (to ensure the lower load limit);
- yellow tip index I_Y (soot formation indicator to ensure the combustion completeness).

The last index makes the environmental criterion in conditions of change the fraction of primary air supplying the burner (particularly – in the ejection devices) under the condition of using the installed burner system by replacement the type of fuel.

The above mentioned characteristics are used in frame of other generalizing criteria: factor C, Knoy formulas, Weaver indexes.

Some other criteria are wide – spread ones for accounting the type of fuel used: Wobbe number, higher and lower – to estimate the carrying capacity of the burners and pipe – lines, and Devecchi number – to account the fuel flammability.

Listed criteria give a possibility to evaluate approximately the expected range of stable combustion by burner operation with fuel ***s*** (substituting) by means of physical modeling or by the tests of the experimental (pilot) or industrial equipment with gas ***a*** (base or adjustment substituted one) (Weber, 1966).

It's obvious that mentioned approach doesn't meet modern conditions and is not sufficient.

To estimate the results of replacement one fuel type for another under application for specific process, the physical and chemical properties of the combustible must be defined. For example in case of the natural gases been extended in Europe the following set of characteristics of fuel gas, combustible-oxidant mixture and combustion products is used (Erdgas-Datenblatt, 2012):

- Total (TCV – higher) Q_h and Net (NCV – lower) Q_l calorific values (combustion heats), MWh/m^3;
- Wobbe numbers (indexes): lower – Wo_l and higher – Wo_h, MWh/m^3;
- fuel gas density ρ, kg/m^3;
- relative (to an air) gas density G;

- methane number MZ;
- air to gas volume stoichiometric ratio (min) L_{st}, m^3/m^3;
- oxygen to gas ratio, stoichiometric (min) O_2, m^3/m^3;
- content (vol.) of main combustion components in wet and dry stoichiometric mixture of combustion products, %;
- specific yield of wet and dry combustion products per unit of gas, m^3/m^3;
- emission factor: specific yield of CO_2, t/TJ;
- "flame" temperature (without dissociation account), K;
- burning velocity of stoichiometric gas-air mixture u_n, m/s;
- ignition temperatures of the mixture in air T_{ig}, K;
- burning limits (limits of flammability) in air, %, vol.

Analyzing the structure of gas consumption and taking into account the modern challenges, the energy and environmental aspects become the defining items by solution the problem of gas supplying. Previous limitations and earlier criteria of gases interchangeability have lost the principal significance and must be changed by more actual characteristics and requirements being represented mainly by power and environmental criteria separately and in combination.

2. STRUCTURE OF ENERGY SOURCES BY ESTIMATION THE OPPORTUNITIES OF NATURAL GAS SUBSTITUTION

The constituents of primary energy sources produced in the World and data on fuel and energy use by branches of application make necessary background by decision the problem on substitution the hydrocarbons by cheaper and more accessible alternative fuels of various origin.

In Table 1 the information is given on total primary energy production and the structure of different energy sources in some European countries. For comparison the respective data are presented for Ukraine, USA and World on the whole. As could be seen the distribution of energy sources in Europe and first of all in European Union countries is distinguished by significant variety. The same statement is related to share of natural gas to be partially substituted by alternative gas fuels (AGF) in future. Type of preferable AGF to be chosen depends on the application purpose of the plant under consideration: for industrial sector – the process gases, for example of metallurgical production, for residential sector – bio-fuels and the gasification products.

Main end – use sectors of primary energy production make the next ones: residential, transportation, industrial and commercial with the trend of growth each of them and the total energy consumption in 2012 – 2035 (AEO, 2012). The largest relative growth for future in USA for example is expected in the commercial sector which currently accounts for smallest share of end use energy demand while the second-largest increase in total primary use.

The industrial sector in USA takes 31 % of total U.S. natural gas use demand (Liss, 2012; NGPO, 2009) while generally the shares of power generation and of industrial sectors account for roughly two – thirds of total U.S. natural gas consumption (Liss, 2012). In both two last mentioned sectors the process gases could be used as AGF: high-temperature fuels like coke oven gas (COG) by any

ISSN 1313-2539, Published at: http://www.scientific-publications.net

industrial or power generation applications while low-calorific, low-temperature fuels like blast furnace gas could be used in municipal and residential sectors.

Accordingly Figure 1 more than 40 % of total natural gas consumption in Ukraine has been spent for purposes of heating the domestic and industrial premises. The industrial sector in Ukraine takes 39 % of total natural gas consumption making the principal share.

Some European countries have an exclusively ambitious intends on reduction of traditional fuels use and their replacement for renewable energy sources and alternative fuels. For example, the Federal Cabinet of Germany has adopted on September 28th, 2010, an energy concept for green-friendly, reliable and accessible energy supply (Marx, 2010).

Mentioned concept guides the energy policy in Germany for next few years. Objective of the energy plan makes reduction to 2020 the greenhouse gases emission by 40% and to 2050 – by 80…95 %. Development of renewable energy sources for power generation is an important part of the plan. The target is provision the share of renewable energy in electricity production of 35 % by 2020 and 80 % by 2050. Primary energy consumption can be halved by 2050 (Marx, 2010).

TABLE 1 Primary Energy Production / Shares of various energy sources in total gross energy consumption by fuel in Europe, 2009; Ukraine, 2009; 2010 in comparison with USA, 2010 (AEO, 2012) and the World, 2007 (AER, 2010) data.

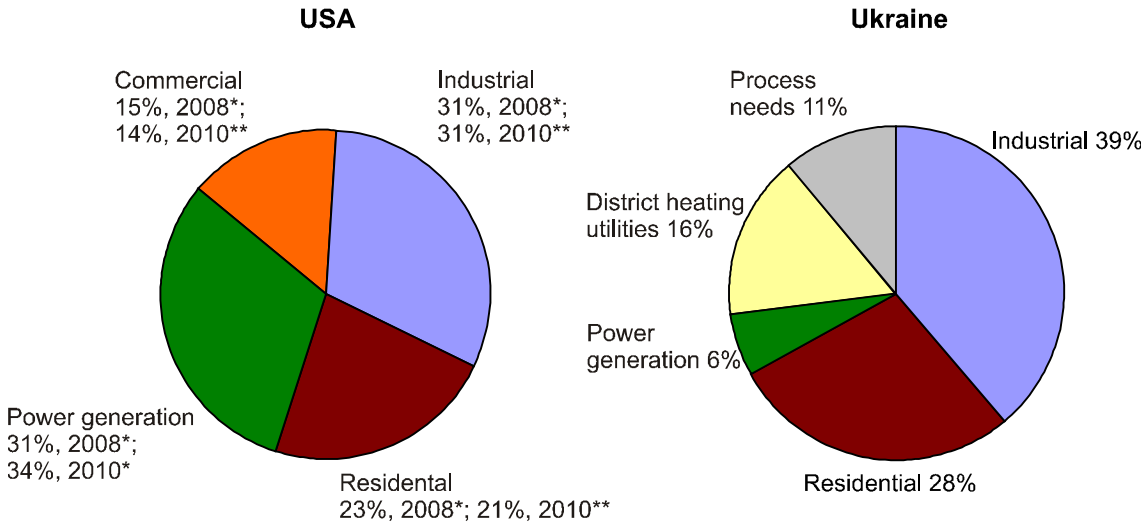
Country	Total Consumed Energy, megatons OE*	Power Source, %						
		Coal	Oil	Natural gas	Nuclear power	Renewables	Industrial waste	Primary energy consumption
Germany	326.6	22.1	34.9	23.6	10.7	8.5	0.5	– 0.3
France	262.7	4.3	33.9	14.7	40.4	7.6	0.0	– 0.9
United Kingdom	206.8	14.3	36.0	37.8	8.6	3.0	0.1	0.1
Italy	168.9	7.6	42.1	38.0	0.0	9.5	0.0	2.3
Spain	130.2	8.1	48.5	24.1	10.5	9.3	0.0	– 0.5
Ukraine, 2009	112.3	30.3	12.2	36.3	19.3	2.2	0.0	– 0.3
Ukraine, 2010	130.52	28.0	10.1	42.3	17.9	2.0	0.0	– 0.3
Turkey	100.0	30.2	31.0	28.9	0.0	9.9	0.0	– 0.1
Poland	95.3	54.1	26.3	12.6	0.0	6.6	0.6	– 0.2
Sweden	45.9	4.2	27.8	2.7	29.6	34.8	0.0	0.9
Finland	34.0	15.8	30.0	10.3	17.9	23.3	0.1	3.1
Greece	30.6	27.5	55.5	9.7	0.0	6.1	0.0	1.2
Hungary	25.3	10.2	28.5	36.3	15.8	7.3	0.1	1.9
Norway	28.8	2.0	39.0	19.1	0.0	42.6	0.1	– 2.7
Switzerland	28.2	0.5	46.4	9.7	25.9	17.2	0.9	– 0.7
USA, 2010	2470	21	37**	25	9	7 1-liquid biofuel	–	–
World, 2007	1195	27.9	35.3	22.9	5.7	8.2	–	–

* 1 ton OE (Oil Equivalent) = 11.630 kWhHi = 41.868 GJ;

** petroleum + other liquids.

Analysis of energy and fuel balances composed of components basing upon net and total heat values of each constituent defined in MtOE (Oil Equivalent) or in Mt of equivalent fuel is insufficient because it deals with the first thermodynamics law only but doesn't take into consideration the second thermodynamics law. It means that relevant researches have been performed disregarding the "quality" of the fuel energy or neglecting the fuel-oxidant mixture potential.

The fuel potential could be presented as a function of adiabatic combustion temperature by means of application the different parameters: efficiency of fuel utilization, process T_{ex} to adiabatic temperature T_T ratio and ratio of specific excess total enthalpies of combustion products taken at T_{ex} and T_T temperatures – respectively.



* NGPO, 2009;
** AEO, 2012.

Source: Ukraine State Statistic Committee (2012)

FIGURE 1 Structure of natural gas end-use consumption in USA, 2008; 2010 and in Ukraine, 2010.

3. STATEMENT THE PROBLEM OF CREATION THE SCIENTIFIC FUNDAMENTALS OF THE FUELS REPLACEMENT

Substitution one fuel for another type or the fuel-oxidant mixture for other one makes complex multifactor problem which causes change of power, technological, environmental (ecological) and operating characteristics of thermal plants. The opportunities of new methodology to be proposed have to assist the solution of applied (including industrial needs, district and local heat supply) tasks. But the universal approaches of updating the problem have not been developed till present.

It's understandable that an option of representative energetic and environmental characteristics of fuels makes the most important constituent of the problem under consideration.

Replacement of fuel – oxidant mixture composition is connected with a change of the following characteristics:

- thermal capacity of plant;
- temperature conditions within the heating (working) space of furnace (boiler);

- efficiency of fuel and heat utilization within the thermal plant;
- carrying capacity of the burners, nozzles and pipe-lines;
- stabilization of flame, range of stable burning by variation the thermal capacity and by change the "fuel : oxidant" ratio;
- flame characteristics, beginning of its geometry and including the optical properties (emissivity, absorptivity);
- emission of harmful substances (NO_x, CO, SO_x, PAH, Soot) and of greenhouse gases (CO_2).

The problem of fuel type replacement is not settled only by change the fuel flow rate in accordance with new calorific value (combustion heat of substituting ***s*** fuel instead of base ("***a***") one). Moreover, in separate cases partial substitution of natural gas for low calorific gases (LCV-gases) sometimes doesn't provide the saving of natural gas but even causes over expenditure of absolute consumption of natural gas. Situation of such kind have occurred by firing the reheating furnaces of rolling mills with the mixture of natural gas and blast furnace gas. New fuel sometimes would not be able to ensure the process on principle. It's explained first of all by necessity to account not only the 1st (energy balance conservation) but also the 2nd thermodynamic law (account of fuel-oxidant potential and energy utilization efficiency) (Kondepudi and Prigogine, 1999). Efficiency has been taken into account by thermal characteristics value related to "hot" source and "cold" heat absorber. In accordance with our approaches we use the energy value (including its chemical constituent) in form of specific excess total enthalpy $\Delta H_{f,T}$ and the exergy $\Delta E_{f,T}$ been computed basing upon total enthalpy of the working (heat transfer) media (Soroka, 1993)**.**

4. CONCEPT AND CONSTITUENTS OF PROPOSED FUNDAMENTALS

The concept of proposed scientific and engineering fundamentals makes providing and supporting the combination of power and environmental components of operation characteristics of the boilers and the industrial furnaces in going from hydrocarbon fuels to low-calorific (alternative) fuels and the fuel mixtures. It necessary to predict the plants' characteristics under operation with any "substituted" and "substituting" fuel gases to provide the proper measures.

Mentioned below constituents of new gas fuels interchangeability fundamentals are included into the proposed background:

1. *Method and computer code of calculation the required consumption of alternative fuel* (***s***) as well as an estimation of environmental impact in the conditions of complete or partial substitution the hydrocarbon fuel taking into account the fuel potential lowering and reduction the combustion temperature for alternative LCV fuel-oxidant mixture, the following characteristics have been proposed as defining values.

- specific heat consumption b_H;
- specific fuel consumption b_f;
- specific issue of harmful substance, for example C_{NOx};
- specific issue of greenhouse gases (C_{CO2}).

2. *New and/or advanced existent and known in the world techniques of calculation the fire engineering characteristics* of alternative gas fuels and of their mixtures with natural gas by means of determination

2.1. Whether a gas under consideration is flammable;

2.2. Limits of flammability (upper and lower limits of flame propagation);

2.3. Burning velocity – laminar flame velocity – or normal speed of flame propagation u_n (S_L);

2.4. Methane number of gas fuel MZ.

3. *Methods and the results of numerical analysis of influence the alternative fuel's composition* and parameters as well as oxidant (air): fuel ratio on

3.1. Heat engineering combustion characteristics of the fuels and mixtures:

- Total (TCV – higher) Q_h and Net (NCV – lower) Q_l calorific value (combustion heat);
- Wobbe number, higher – Wo_h and lower – Wo_l;
- Devecchi number;
- molar, volume L_{st} and mass Ω_{st} stoichiometric ratio;
- theoretical (adiabatic) combustion temperature T_T;
- fuel and heat utilization efficiency – depending on parameters of thermal process.

3.2. Thermodynamic equilibrium composition of combustion products (up to 100 components), including the content of harmful species (NO_x, CO, SO_x) and greenhouse gases (CO_2);

3.3.Heat-and-power engineering and heat physical (transport) properties of combustion products:

- coefficient of dynamic and kinematic viscosity;
- coefficient of heat conductivity;
- thermal diffusivity;
- degree of blackness (radiative ability) and specific radiation flux.

3.4. Thermodynamic properties of combustion products in dependence on temperature and pressure:

- specific volume;
- molar mass M;
- characteristic gas constant;
- specific heat capacity at constant pressure and at constant volume;
- specific values of enthalpy H and entropy E;
- dew point T_r.

4. *The original author's computer codes on combustion thermodynamics and kinetics*, providing calculation of above mentioned characteristics of the gases under consideration in the conditions of

substitution the hydrocarbons (natural gas) for alternative fuels have been developed in the Gas Institute, NASU.

Thus, list of appropriate characteristics of the fuels and combustion products proposed to define in frame of our fundamentals is wider and more representative than suited to European gas fuels (Erdgas-Datenblatt, 2012). For example, the adiabatic (theoretical) combustion temperature is more physical value than "flame" temperature, calculated without dissociation account (Erdgas-Datenblatt, 2007). Specific yields of pollutants (C_{NOx}, C_{CO2}) are more adequate values than those mentioned above in paragraph "State-of-the-art" because the pollutants yield by our approach is defined with account of the process or plant efficiency.

Comparison of some characteristics of fuel gases defined by our original techniques and taken from reference publications (Erdgas-Datenblat, 2007; Erdgas-Datenblat, 2012) is presented in Tables 2 and 3.

In Table 2 are given the results of our calculation the main heat engineering characteristics of fuels, as an example of the natural gases extended in Europe (subscript "calc") and the values taken from German reference data (Erdgas-Datenblatt, 2012). These data are concerned Net (lower) Q_l and Total (higher) Q_h calorific value (combustion heat).

TABLE 2 Main heat engineering characteristics of European natural gases accordingly E.ON – Ruhrgas data (Erdgas-Datenblatt, 2012) and by our computations (*calc*)

Composition	Types of European natural gases					
Parameter,	Erdgas H			Erdgas L		
Dimensions	Nordsee	Misch	Russ.	Holland	Verbund	Weser/Ems
CH_4, vol.%	90.4	91.18	97.01	83.14	84.46	85.16
N_2, vol.%	0.94	1.27	0.83	11.17	10.70	10.83
CO_2, vol.%	1.67	1.57	0.17	1.56	1.66	1.85
C_2H_6, vol.%	5.72	4.98	1.41	3.29	2.56	1.79
C_3H_8, vol.%	1.13	0.74	0.43	0.53	0.39	0.24
C_4H_{10}, vol.%	0.30	0.20	0.13	0.18	0.13	0.09
C_5H_{12}, vol.%	0.08	0.04	0.02	0.07	0.04	0.02
C_6H_{14}, vol.%	0.03	0.02	0.01	0.06	0.05	0.03
T_T, K	2224	2222	2222	2209	2208	2206
Q_h^{ref}, kWh/m^3	11.57	11.37	11.19	10.10	10.03	9.88
Q_h^{calc}, kWh/m^3	11.46	11.27	11.08	10.03	9.95	9.80
δQ_h, %	0.95	0.88	0.98	0.69	0.80	0.80
Q_l^{ref}, kWh/m^3	10.45	10.27	10.09	9.12	9.05	8.91
Q_l^{calc}, kWh/m^3	10.36	10.18	10.00	9.05	8.98	8.84

δQ_l, %	0.86	0.88	0.89	0.77	0.77	0.79
Wo_h^{ref}, kWh/m^3	14.67	14.54	14.77	12.60	12.59	12.45
Wo_h^{calc}, kWh/m^3	14.59	14.45	14.68	12.54	12.51	12.37
δWo_h, %	0.54	0.62	0.60	0.48	0.62	0.64
Wo_l^{ref}, kWh/m^3	13.26	13.13	13.32	11.37	11.36	11.22
Wo_l^{calc}, kWh/m^3	13.19	13.06	13.24	11.32	11.29	11.16
δWo_l, %	0.53	0.53	0.60	0.44	0.64	0.53

Note: $\delta Q = (1 - Q^{calc} / Q^{ref}) \cdot 100\%$; $\delta Wo = (1 - Wo^{calc} / Wo^{ref}) \cdot 100\%$;

The comparison of experimental data of u_n^{ref} with that u_n^{calc} accordingly our calculations for the case of combustion of the air mixtures of the natural gases from different gas fields is shown in the Table 3. The discordance $\delta u_n = (1 - u_n^{calc} / u_n^{ref}) \cdot 100\%$ of the German measured data (Erdgas-Datenblatt, 2007) and of our predicted values doesn't exceed 4.65%.

Checking of two-parametric MF generalization to calculate u_n of six European natural gases (Table 3) has been conducted in methodological work by B. Soroka (Soroka, 2009). Good accuracy of burning velocity definition of stoichiometric ($\lambda = 1.0$) cold air mixtures of natural gases of high ($[CH_4] > 80\%$) methane content has been shown.

All the thermodynamic calculations have been performed by means of our original computer code "FUEL" connected with searching for equilibrium state of reacting system, definition of properties of the mixtures of chemically equilibrium components. The technique is based upon supporting the condition to meet the Gibbs' energy change of the system $dG = 0$ by reaction proceeding (Warnatz *et al.*, 2001).

As the main energy characteristic the total enthalpy H, accounting energy of the component(s) formation, was used for the process occurrence by the p = const (isobaric process) or excess enthalpy ΔH at current temperature T_{in} respect to that at basic (standard) temperature T_0.

By our calculations the Net (NCV) and Total (TCV) calorific values (combustion heat) were defined accordingly inquiry definitions of these fuel parameters by means of application the thermodynamical properties of equilibrium combustion products at theoretical combustion temperature T_T and at standard temperature 298 K (25 ºC) as the zero reading for the specific total enthalpies values. The same basic temperature for computations the combustion processes is recommended by reference (Erdgas-Datenblat, 2007; Erdgas-Datenblat, 2012).

Our technique of calculation the NCV and TCV is considered in the next section.

TABLE 3 Comparison of burning velocities u_n and dew point values T_r accordingly E.ON – Ruhrgas data (Erdgas-Datenblatt, 2007) and by our computations (*calc*)

Composition	Types of European natural gases					
Parameter,	Erdgas H			Erdgas L		
Dimensions	Nordsee	Misch	Russ.	Holland	Verbund	Weser/Ems
CH_4, vol.%	87.18	87.50	97.63	83.08	85.46	88.08
N_2, vol.%	0.92	2.65	0.83	9.21	9.21	8.71
CO_2, vol.%	1.99	1.96	0.09	1.74	1.74	2.55
C_2H_6, vol.%	7.96	6.80	1.00	3.97	2.91	0.61
C_3H_8, vol.%	1.58	0.90	0.32	0.81	0.47	0.04
C_4H_{10}, vol.%	0.30	0.16	0.11	0.22	0.15	0.01
C_5H_{12}, vol.%	0.05	0.02	0.01	0.06	0.03	<0.01
C_6H_{14}, vol.%	0.02	0.01	0.01	0.04	0.03	<0.01
u_n^{ref}, m/s	0.43	0.43	0.43	0.41	0.41	0.41
u_n^{calc}, m/s	0.415	0.412	0.410	0.407	0.406	0.402
δu_n, %	3.49	4.19	4.65	0.73	0.98	1.95
T_r^{ref}, K	332.04	332.13	332.55	332.06	332.18	332.37
T_r^{calc}, K	332.74	332.86	333.27	333.27	332.91	333.12
δT_r, %	0.21	0.22	0.22	0.36	0.22	0.23

Note: $\delta u_n = (1 - u_n^{calc} / u_n^{ref}) \cdot 100\%$; $\delta T_r = (1 - T_r^{calc} / T_r^{ref}) \cdot 100\%$;

5. SOME EXAMPLES OF APPLICATION THE TECHNIQUE OF THE FUEL SUBSTITUTION

Accordingly proposed concept all the proper procedures are carried out with *thermodynamically equilibrium combustion products* of the considered fuels (Soroka, 1993; Soroka and Sandor, 2000).

The similar assumption regarding the state of working medium has been made by the authors (Ptasinski *et al.*, 2006) by evaluation the exergetic efficiencies for idealized gasification installation in which chemical equilibrium is attained.

Main power criteria defining energy and fuel consumption in the plant by comparison the fuels make *efficiency of fuel utilization and of heat utilization* – both in form of useful fraction of enthalpy and exergy.

1. The calculations are performed by plant consideration as *"ideal furnace"* with the single form of heat losses – heat removed of the furnace with flue gases ("*fl*") at the exit cross-section of plant ("*ex*"). The following efficiencies of the plant accordingly our developments (Soroka, 1993) have been obtained and used:

- for fuel utilization:

$$\eta_f^{id} = \frac{\Delta H_{f,T} - \Delta H_{f,ex}}{\Delta H_{f,T}^*} \quad (1)$$

- for energy utilization:

a) heat efficiency

$$\eta_H^{id} = 1 - \frac{\Delta H_{f,ex}}{\Delta H_{f,T}} \quad (2)$$

b) exergy (serviceability) efficiency

$$\eta_{eff} = 1 - \frac{\Delta E_{ex}}{\Delta E_T} = 1 - (\Delta H_{f,ex} - T_0 \int_{T_0}^{T_{ex}} T^{-1} dH_{f,fl}) / (\Delta H_{f,T} - T_0 \int_{T_0}^{T_T} T^{-1} dH_{f,fl}) \quad (3)$$

The comparative data on plant efficiencies by natural gas (NG) and blast-furnace gas (BFG) combustion are presented in Figures 2, a – d in dependence on operation temperature T_{fl}. The condition of provision the equal temperature values for the combustion products within the plant and the flue gases at the plant exit $T_{ex} = T_{fl}$ is assumed by carrying out the computations under substitution one fuel for another one.

Mentioned data in Figure 2 demonstrate the significant increase of any of compared efficiency values η_f, η_H, η_{eff} for the case of NG using against the respective values for BFG. The higher are the operation temperatures (T_{ex}), the more would be the differences of the efficiency values by compared fuels application.

2. Evaluation of the alternative fuels in comparison with the fossil fuels is provided by both *power and environmental criteria*. First of mentioned characteristics is presented by *furnace efficiency on fuel utilization* and by inverse value – by specific fuel heat consumption b_f; the second criteria is determined by toxic substances concentration in flue gases and by *specific toxic substances formation* C_t (particularly $t \equiv NO_x$). Both criteria are related to the unit of the plant production (output of the industrial furnaces) or unit of energy produced (power generating systems with the boilers).

Thermodynamic analysis has the advantage of providing the selection of accessible, inexpensive fuels, which allow generation of power or implementation of an industrial process under ensuring the requirements of saving expensive hydrocarbon fuel (natural gas or fuel oil). The widely available gaseous by-products of metallurgical plants (process gases: coke-oven, blast-furnace, converter gases and the mixtures of the mentioned gases with natural gas) can be used in power-generation plants and in the industrial furnaces (Soroka and Sandor, 2000). Feasibility of a given fuel application depends on the relationship between available potential $\Delta H_{f,T}$ of the fuel mixture and the required enthalpy $\Delta H_{f,fl}$ of heat-transfer medium while process efficiency makes a function of the operating temperature of the process under consideration (T_{ex} – for "ideal" equipment (furnace)).

ISSN 1313-2539, Published at: http://www.scientific-publications.net

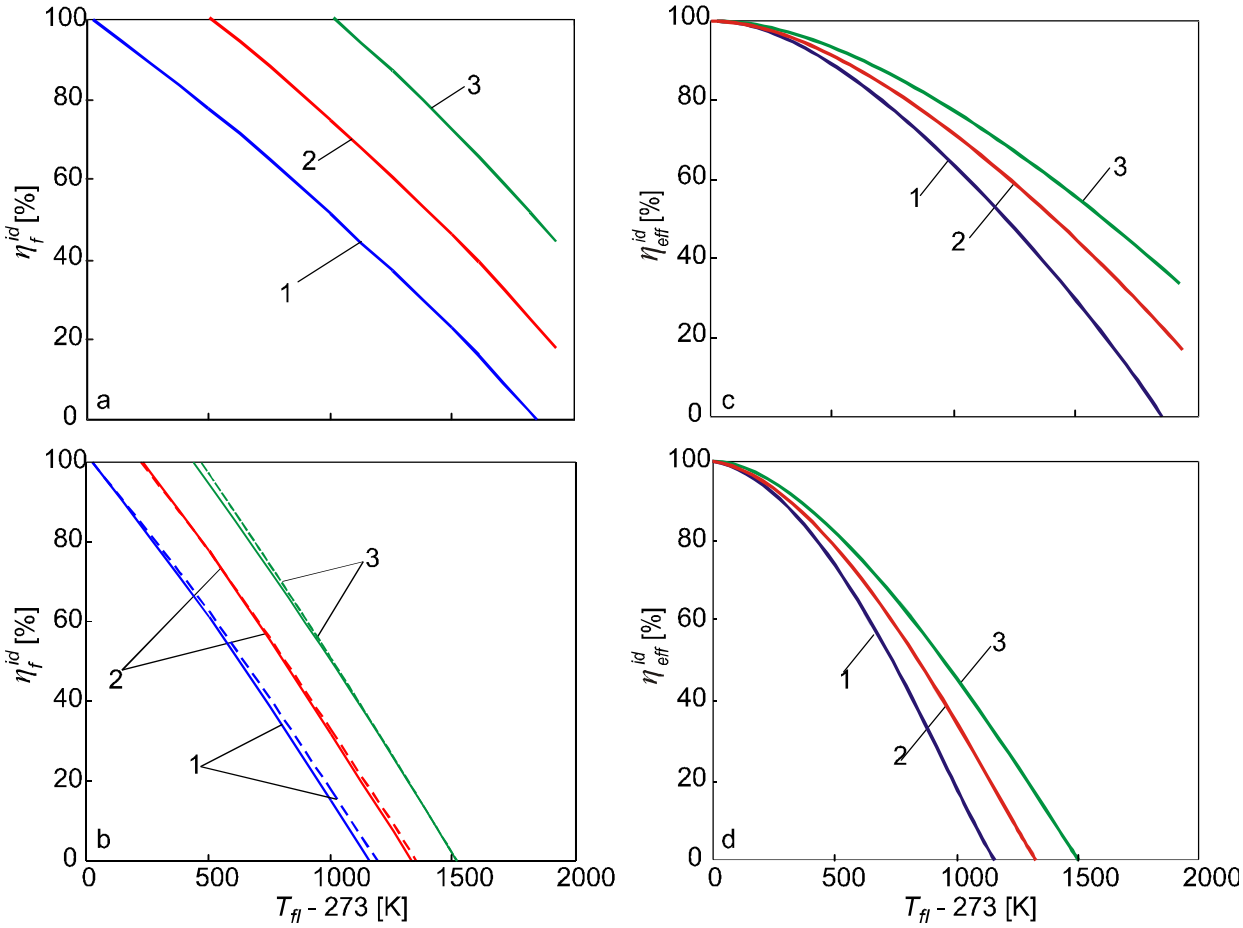


FIGURE 2 Dependence of fuel utilization efficiency η_f^{id} (a, b) and exergy efficiency η_{ef}^{id} (c, d) on exit temperature of flue gases T_{fl} by combustion of air mixture of natural gas (a, c) and that of blast–furnace gas (b, d). Combustion air preheating temperature, K (°C): 1 – 298 (25); 2 – 873 (600); 3 – 1473 (1200). Air excess factor λ: dotted lines – 1.0; solid lines – 1.1.

In some cases when using mixtures of the aforesaid gases with natural gas it is found that instead of the expected fuel saving the absolute consumption of natural gas in mixture is actually higher than by using the single natural gas. Let us assume that, in order to implement a process of temperature T_{ex} it is necessary to burn the fuel flow rate B_{f1} if using fuel with component 1 only. In the case of joint combustion of two fuels: f_1 and f_2, the consumption of component 1 changes by the absolute amount ΔB_{f1} and relative value δB_{f1} in the mixture in comparison with B_{f1}.

The variation in absolute consumption of one of the fuel components – designated as f_1 (for example, natural gas) when used jointly with another component in the mixture (the mixed fuel would be designated f_{1+2}) – can be estimated by means of numerical solution the equation for the relative change of consumption of fuel 1 obtained from the enthalpy balance of the fuel-using plant ("ideal" furnace):

$$\delta B_{f1} = \frac{1}{(1+\Delta B\%)}\left(\frac{\Delta H_{f1,T} - \Delta H_{f1,ex}}{\Delta H_{f1+2,T} - \Delta H_{f1+2,ex}} - 1\right), \qquad (4)$$

where $\delta B_{f1} = \Delta B_{f1} / B_{f1}; \Delta B^{\%} = B_{f2} / \Delta B_{f1}$.

The minus sign for δB_{f1} designates the relative saving component's 1 flow rate when it is mixed with component 2, whereas the "+" sign designates over-expenditure of component 1. However, in some cases, saving of natural gas by substitution by another fuel cannot be reached. These cases are related to mixing the natural gas with low calorific (LCV) gases.

Some results on influence the fuel mixture composition on consumption of natural gas being mixed with process gases is considered in Figures 3 basing upon thermodynamic approach. Not each of the alternative fuels could be used for the steel preheating because this process is related to the high-temperature treatment operation.

As could be stated from consideration the Figures 3, an opportunities of reduction the natural gas (NG) consumption in the mixture with the process gas is limited in case of low-calorific gases (blast–furnace gas (BFG)) within the range of comparatively low operation temperatures – below T_{fur} = 1450 K.

Any heat (enthalpy) saving is not observed and continuous over expenditure of required heat is marked for the case of BFG – NG mixture combustion due to admix the BFG to NG within the temperature range $T_{fur} \in \{800; 1600\ K\}$. In case of high-temperature coke-oven gas combustion jointly with the natural gas, NG saving as well as the required heat (enthalpy) reduction would be fixed by any furnace process temperature $T_{fur} \in \{800; 2200K\}$. Similar analysis and results have been obtained by Chinese authors (Vestenberg *et al.*, 2007) but many years later than we've proved this statement (Soroka and Sandor, 2000).

3. Advancement the problem of interchangeability of fuel gases was carried out particularly in frame of studying the possibilities to increase the natural gas (NG) flow rate by means of dilution the natural gas with alternative gas fuels (AGF). Estimation of substitution opportunities of one fuel type for another has been testified, and the limits of replacement the NG by some LCV gases were defined accordingly official norms for natural gas (NG) acting in Ukraine. The same standards are serving in other states of Independent Countries Union (former Soviet Union). Accordingly state standard (norms) GOST 5542-87 "Combustible natural gases for industrial and municipal purpose" prolonged by action in 2010 action for indefinite period, the restrictive demands for NG characteristics are concerning the following parameters:

3.1. Limit (maximum) O_2 concentration in gas – no more than 1% (vol.).

3.2. Minimal limit for NCV – Net Calorific Value (lower combustion heat value) – no less than $Q_{l,min}$ = 31.8 MJ/m^3 by 298 K (20 ºC) temperature and 1.01325 bar atmospheric pressure while combustion heat value of NG, supplying by means of cross-country gas pipe-line, makes $Q_l \approx$ 33.6 MJ/m^3 as a rule. Accordingly European data for Russian natural gas the Total (TCV) and Net (NCV) calorific values make Q_h = 40.28 MJ/m^3 (11.19 MWh/m^3),
Q_l = 36.32 MJ/m^3 (10.09 MWh/m^3) – respectively by 273 K (0 ºC) and 1.01325 bar conditions for gas volume (Erdgas-Datenblatt, 2012).

Calculation of Net (NCV – lower) Q_l and Total (TCV – higher) Q_h calorific value (combustion heat) has been performed in accordance with definitions (White, 1966).

Net calorific value (NCV), Q_l: number of Btu evolved by the compete combustion at constant pressure of one standard cubic foot of gas with air; temperature of gas, air, and products of combustion being 60 F (288.5 K), all water formed by combustion reaction remaining in the vapor state.

ISSN 1313-2539, Published at: http://www.scientific-publications.net

Total calorific value (TCV), Q_h: number of Btu evolved by the compete combustion at constant pressure of one standard cubic foot of gas with air; temperature of gas, air, and products of combustion being 60 F (288.5 K), all water formed by combustion reaction being condensed to liquid state.

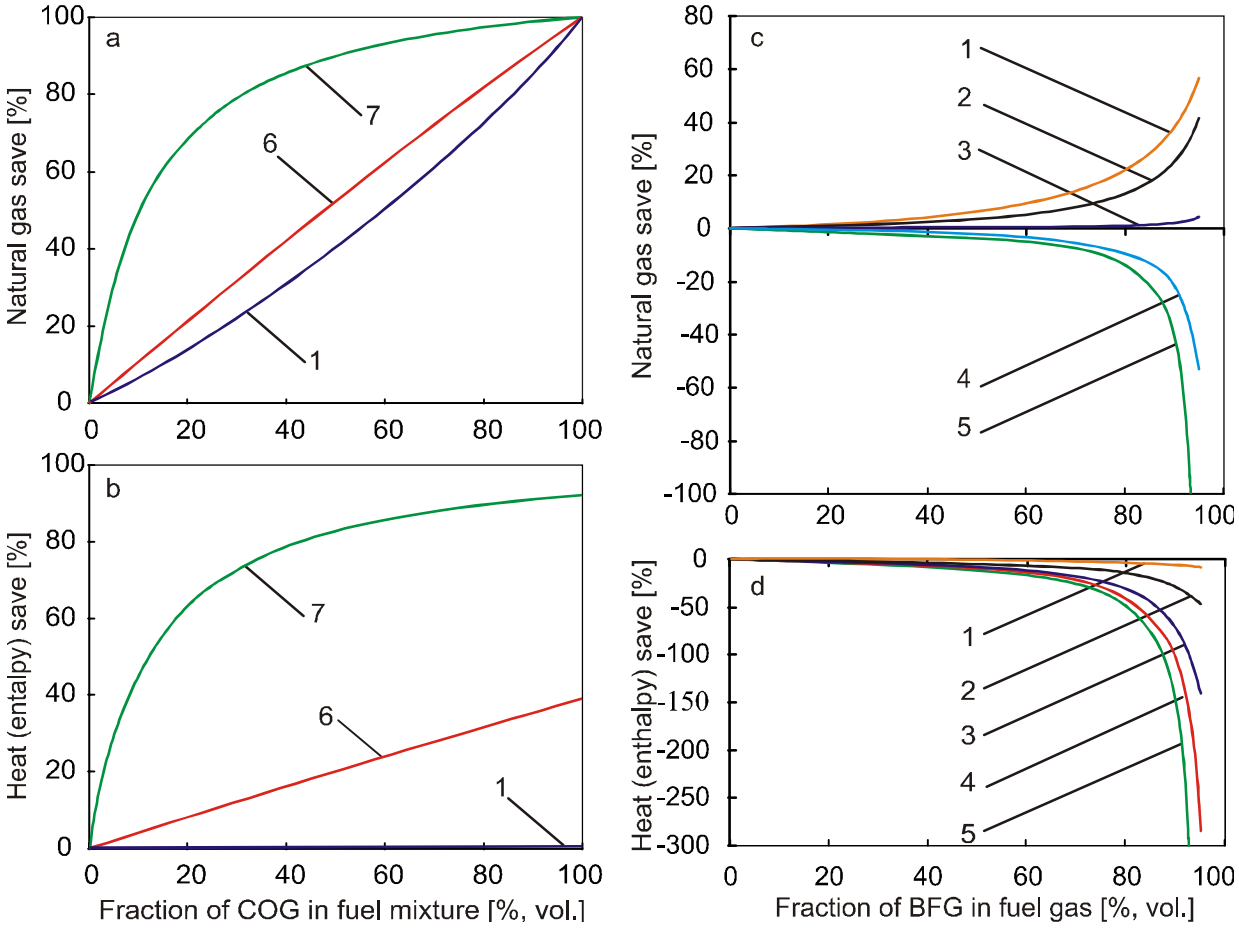


FIGURE 3 Influence of admixing the process gases: coke-oven gas (COG) (a, b) and blast furnace gas (BFG) (c, d) – to natural gas (NG) on NG saving or overexpenditure (a, c) and heat (enthalpy) save (+) (overexpenditure (–)) (b, d) in dependence on fraction of process gas in mixture with NG. Furnace process temperature T_{fur} = T_{fl} = T_{ex}, K: 1 – 800; 2 – 1200; 3 – 1450; 4 – 1550; 5 – 1600; 6 – 2100; 7 – 2200.

By our numerical calculations and comparison with European gases characteristics (Erdgas-Datenblatt, 2012) the combustion heat values were related to the composition of gases given in Tables 2 and 3, considered gas amount – 1 m^3 taken at 273 K (0 ºC) and atmospheric pressure 1.01325 = 101.325 kPa bar while total enthalpies of equilibrium combustion products mixture are computed at theoretical combustion temperature T_T and at basic standard temperature 298 K.

The calculation procedure of Q_l and Q_h searching in conformity with aforesaid definitions has been proposed and performed:

$$H_{\Sigma in,T_o} = H_{\Sigma prod,T_o}; \quad (5)$$

$$H_{\Sigma in,T_o} - H_{\Sigma prod,T_o} = \Delta H_{T_0}; \quad (6)$$

$$H_{\Sigma prod,T_T} - H_{\Sigma' prod,T_o} = Q_l; \quad (7)$$

$$H_{\Sigma prod,T_T} - H_{\Sigma'' prod,T_o} = Q_h, \quad (8)$$

where $\Sigma prod, T_0$ – equilibrium combustion products including equilibrium H_2O (liquid + vapor) at T_0; $\Sigma' prod, T_0$ – combustion products including total H_2O in vapor phase at T_0; $\Sigma'' prod, T_0$ – combustion products including total H_2O mass liquid phase (water) at T_0.

3.3 Range of Higher Wobbe numbers Wo_h calculated through TCV – Total Calorific Value Q_h:

$$Wo_h = Q_h / G^{0.5} = Q_h / (M_f / M_a)^{0.5} \quad (9)$$

makes 41.2…54.4 MJ/m^3 by above mentioned conditions for m^3.

The feasible admixtures of alternative gas fuels (AGF) to NG without violation the standard's requirements could be proposed as a means of increase the fuel flow rate basing on minimal values of two last mentioned limitations: Q_l and Wo_h – see Figures 4 and 5. The ranges of acceptable Q_l and Wo_h standing rule values for NG in accordance with GOST 5542-87 are darkened in both mentioned Figures.

The Figures 4 and 5 illustrate the procedure of definition the possible limits of admixing to NG of the AGF presented by LCV-gases: syntheses SG1, SG2 and biogases BG1, BG2. The values of parameters to be estimated for the fuel mixtures are defined as weighted sums of respective parameters of fuel components:

$$Q_{h,mix} = Q_{h,NG}\, D_{NG} + Q_{h,AGF}\, D_{AGF}; \quad (10)$$

$$M_{f,mix} = M_{f,NG}\, D_{NG} + M_{f,AGF}\, D_{AGF}; \quad (11)$$

$$G_{f,mix} = G_{f,NG}\, D_{NG} + G_{f,AGF}\, D_{AGF}. \quad (12)$$

Generally, for each of parameters $X_{f,mix} \in \{ H_{T,mix}; M_{f,mix}; G_{f,mix} \}$ to be estimated:

$$X_{f,mix} = D_{NG}\, (X_{f,NG} - X_{f,AGF}) + X_{f,AGF} \quad (13)$$

The characteristics $X_{f,mix}$ of AGF and NG gases forming the mixtures are collected in Table 4 along with the gases compositions.

To realize the procedures all the data presented in Figures 4 and 5 are reduced to the normal m^3 of mixed gas (Nm^3 – taken at 273 K (0 ºC) like is adopted in recommendations (Erdgas-Datenblat, 2006; Erdgas-Datenblat, 2007; Erdgas-Datenblat, 2012).

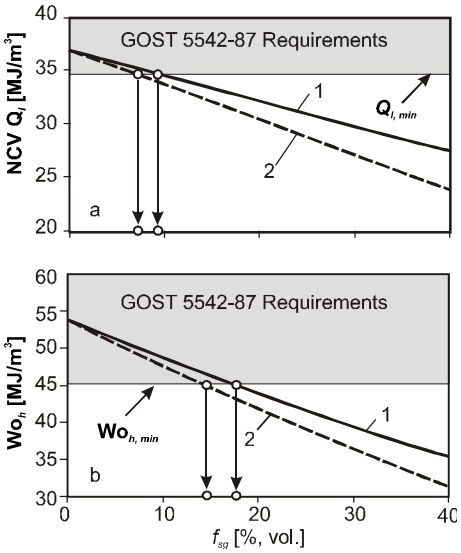


FIGURE 4 Dependence of main characteristics of fuel gases mixture (natural gas (NG) + synthesis gas (SG)) on volume fraction of synthesis gas f_{sg}, % (vol.), to define limit content of SG in mixture that meets the standard's GOST 5542-87 requirements: a – by Net Calorific Value (NCV) Q_l; b – by Higher (Total) Wobbe Number Wo_h. Substituting gas: 1 – synthesis gas SG 1 (gasification products of wood waste); 2 – synthesis gas SG 2 (products of air gasification of wet wood).

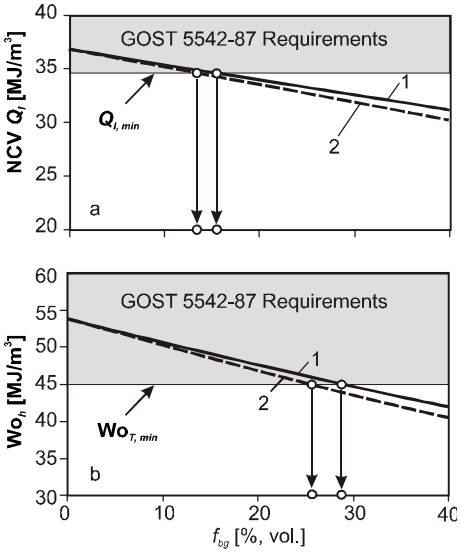


FIGURE 5 Dependence of main characteristics of fuel gases mixture (natural gas (NG) + biogas (BG)) on volume fraction of biogas gas f_{bg}, % (vol.), to define limit content of BG in mixture that meets the standard's GOST 5542-87 requirements: a – by Net Calorific Value (NCV) Q_l; b – by Higher (Total) Wobbe Number Wo_h. Substituting gas: 1 – biogas BG 1; 2 – biogas BG 2.

The lower permissible values of Q_l (a) and of Wo_h (b) are taken from GOST 5542-87 298 K (20 ºC) and recalculated for 273 K (0 ºC).

Basing on two last mentioned limitations the feasible admixtures of alternative gases (AGF) to NG could be defined and proposed without violation the standards – see Figures 4 and 5.

Range of available addition the synthesis gases produced by wood gasification is shown in Fig. 4, a, b and the same for biogases – in Fig. 5, a, b. Composition of AGF-gases both for synthesis and biogases are tabulated (Table 4) along with other necessary data been used to make the estimations of acceptable admixtures to NG in frame of acting standard.

Analysis of presented data has shown that the demand for provision the limitations by $Q_{l,min}$ is much more strict than by $Wo_{h,min}$ numbers. The admissible content of AGF-gases in mixture with NG could be maintained at the fraction value up to 30 % from the standpoint of regulated Wo_h numbers while from the Q_l values the NG fraction in the gas mixture exceeds 90 % for any evaluated AGF-gases.

TABLE 4 Main characteristics of alternative gases to estimate the replacement potential in frame of NG standard

#	Properties			Synthesis gases		Biogases		Natural gas
				SG1	SG2	BG1	BG2	NG
1	Composition	CH_4	Dimensions of quality, % vol.	10.48	2.67	62.99	55.69	95.82
		C_2H_6		1.30	0.09	0.0	0.0	2.812
		C_2H_4		4.03	0.0	–	–	0
		C_3H_8		0.0	0.05	0.005	0.004	0.779
		C_4H_{10}		0.0	0.0	0.007	0.005	0.202
		C_5H_{12}		0.0	0.0	0.02	0.037	0.028
		H_2		10.02	13.11	–	–	0.0
		CO		41.10	14.20	0.0	0.0	0.0
		C_6H_{14}		0.0	0.0	0.06	0.24	0.03
		N_2		14.34	52.97	12.29	20.68	0.149
		CO_2		17.54	14.36	22.44	19.60	0.0
		O_2+Air		1.18	2.6	2.188	3.75	0.028
2	Relative density G		–	0.93	0.92	0.83	0.854	0.577
3	Q_h		MJ/m^3	13.54	4.54	25.02	22.5	40.90
	Q_l		MJ/m^3	13.18	4.18	22.54	20.3	36.94
4	Wo_h		MJ/m^3	14.04	4.75	27.40	24.34	53.86
	Wo_l		MJ/m^3	13.64	4.36	27.70	21.96	48.60
6	Volume stoichiometric ratio L_{st}		m^3/m^3	2.94	0.79	5.91	5.23	9.83
7	Mass stoichiometric ratio Ω_{st}		kg/kg	3.16	0.86	7.10	6.13	17.04

Note: heat values are given at 298 K (25 ºC) for 1 Nm^3 at 273 K (0 ºC) (Erdgas-Datenblatt, 2012)

6. INDUSTRIAL OPTIMIZATION OF FUEL FURNACES

The theoretical statements were validated by our testing of two multi-zone reheating furnaces of pusher type being of 170 t/hour nominal output in Hungary. The following gaseous fuels were compared by firing of the furnaces equipped with the radiant burners: under combustion of natural gas, of coke-oven gas along with the case of using the mixtures of the natural gas with coke-oven gas or of the natural gas with the blast-furnace gas. Combustion air was initially preheated till 573…623 K

(300…350 °C). In the 90-th years the new types of recuperators have been installed, providing air preheating till 803 K (530 °C).

The following conclusion, being fairly coincided with the theoretical results and described above, were made basing upon industrial investigations: the higher is the combustible mixture's potential, the lower would be specific fuel (fuel heat) consumption b_f. The fuel-oxidant mixture potential is defined by the excess total enthalpy of the unit of combustion products $\Delta H_{f,T}$, kJ/kg, under theoretical combustion temperature T_T.

By this reason if the furnace is firing with coke-oven gas b_f is approximately 20…25 % less than by firing with natural gas under supporting the other process parameters in the furnace (output, characteristic temperatures), at the same value. The industrial and thermodynamic calculations data for this case have been collected and analyzed in the presentation (Soroka and Sandor, 2000).

Use of the mixture of the natural gas with the blast-furnace gas is not efficient from the standpoint of natural gas saving for reheating furnace. Over-expenditure of the absolute flow rate of natural gas has been arisen by use of fraction of blast-furnace gas 50 % and more in the mixture with natural gas. The same results could be seen from the thermodynamic calculations data (Figures 3).

By carrying out the combined power and environmental optimization of the furnaces, the dependences of specific fuel consumption b_f and specific NO_x formation – C_{NOx} have been evaluated in dependence on the furnace output G_{fur} value. Fuel heat consumption b_f makes the following values at G_{fur} = 160…200 t/hour under air preheating 573 K (300 °C): 1.55 MJ/kg – by firing the furnace with straight (pure) natural gas; 1.62…1.96 MJ/kg – by use the mixture of natural gas with the blast-furnace gas, including input in the last value of 1.45…1.77 MJ/kg – the share related to natural gas fraction in the mixed gas;

- the higher is the combustible mixture's potential, the higher is NO_x concentration ($[NO_x]$) at the furnace exit under conservation of other parameters at the same level. For example, $[NO_x]$ concentration may be less by 40 % on the average when heating the furnace with natural gas against $[NO_x]$ value by coke-oven gas combustion. Consideration of NO_x formation in terms of C_{NOx} smoothes down the divergence between mentioned indices by comparison the characteristics of combustion products of natural and coke-oven gases;
- the strong dependences of the main furnace indices: b_f and C_{NOx} – on the furnace output G_{fur} has been stated. It was found the similarity of the dependences b_f – G_{fur} (main power performance) and C_{NOx} – G_{fur} (main environmental performance);
- minimal values of the mentioned indices (b_f and C_{NOx}) meet the optimal furnace output, but sometimes the value of the last $G_{fur,opt}$ exceeds the region of real furnace operation and of output range. Region of optimal output $G_{fur,opt}$ is the same for both indices: energetic (fuel utilization) and environmental.

As a result the furnace operation by optimal output makes the simplest method of b_f and C_{NOx} substantial (up to 2 and more times) reduction without any improvement of the furnace design.

CONCLUSIONS

Purpose of elaboration the modern approaches to adequate gas fuels replacement is to account and provide up-to-date requirements to the processes and the plants of fuel use, mainly in power and industry, independently of combustible fuel type.

New scientific and engineering fundamentals of fuels substitution have been developed *instead* of obsolete methodology "Interchangeability of Fuel Gases" developed in USA and existent from the middle of XX-th century *or in addition* to the generalizing criteria been collected in the previous approaches on fuels replacement. Energy efficiency demand and the stringent environmental norms by replacement the hydrocarbon fuels (natural gas – NG) by accessible low-calorific fuels.

To perform the complex prediction of the opportunities and consequences of total or partial substitution of the necessary amount of natural gas NG for alternative gases AG, the following parameters have been proposed to compute and take into account: plant utilization efficiencies – regarding fuel and energy utilization, the last in form of heat η_H and exergy η_{eff} efficiencies; saving or over expenditure of the NG flow rate in the gas mixture with AG, specific fuel consumption b_f and specific issue of harmful substances C_t – pollutants in the combustion products: C_{NOx}, C_{CO2} – as the toxic and greenhouse components respectively. Specific power (fuel use) b_f and environmental C_t indices in this case are related to the unit of useful energy or to unit of the plant output.

Certification of alternative gas fuels and fuel mixtures as a commodity products is carried out in frame of our approach with necessary set of characteristics, similar to those accepted in the world practice (see list of characteristics of natural and alternative gases at the European market) (Erdgas-Datenblatt, 2006; Erdgas-Datenblatt, 2007; Heroin, 2007].

NOMENCLATURE

AGF	alternative gas fuels
B	fuel consumption, kg/s
b_f	specific fuel heat consumption, MJ/kg
BFG	blast-furnace gas
BG	biogas
b_H	specific heat consumption, MJ/kg
COG	coke-oven gas
C_t	pollutive substance "***t***" concentration, ppm
E, ΔE	value and excess value of specific total exergy, kJ/kg
H, ΔH	value and excess value of specific total enthalpy, kJ/kg
G	relative density
G_{fur}	furnace output value, t/hour
I_F	flashback index
I_L	lifting index
I_Y	yellow tip index
LCV	low-calorific gases
L_{st}	air to gas volume stoichiometric ratio (min), m^3/m^3
M	molar (molecular) mass, g/mol
MZ	methane number

NG	natural gas
OE	oil equivalent
Q	calorific value (combustion heat), MJ/m^3, kWh/m^3
SG	synthesis gas
T	temperature, K
TCV	total calorific value
u_n	normal (laminar) flame propagation velocity, m/s
Wo	Wobbe number (index)
X	parameter to be estimated
$[X_t]$	specific yield of pollutants harmful substances (toxic and greenhouse gases)
η_{eff}	exergy (serviceability) efficiency, %
η_f	efficiency of fuel utilization, %
η_H	heat efficiency, %
λ	air excess factor
Ω_{st}	mass stoichiometric ratio

Subscripts and Superscripts

calc	calculation results
ex	exit cross-section of plant
f	fuel
fl	flue gases
fur	for condition within the furnace
h	total (higher) calorific value (combustion heat)
id	ideal furnace
in	initial combustion components (fuel+oxidant)
l	net (lower) calorific value (combustion heat)
min	minimal value
mix	mixture
opt	optimal output
prod	combustion products
r	dew point
ref	literature data
	at theoretical combustion temperature T_T
T	

REFERENCES

(AEO) Annual Energy Outlook, Early Release Reference. (2012) U.S. Dept of Energy, Energy Information Administration, 239 p.

(AER) Annual Energy Rewiew. (2010) U.S. Dept of Energy, Energy Information Administration, 408 p.

Erdgas-Datenblatt. (2006) Wärmetechnische Daten und Begriffe. *GasWärme Intern*., vol. **54**, No. 8, S. 586.

Erdgas-Datenblatt. (2007) Wärmetechnische Daten und Begriffe. *GasWärme Intern.*, vol. **56**, No. 6, S. 445–446.

Erdgas-Datenblatt. (2012) Erdgas – Durchschnittswerte 2011 (E.ON – Ruhrgas). *GasWärme Intern*. **5**, S. 110.

Fossum M. and Beyer R.V. (1998) Co – combustion: Biomass Fuel Gas and Natural Gas. SINTEF Energy Research: Technical Report. Trondheim, Norway, 26 p.

Heroin G. (2007) Stromerzeugung aus Schwachgas nittels Gasmotoren. *Jenbacher Gas Engines, Leipzing.* European experience on recovery of waste energy potential of industrial gases, http: www.Cogeneration.com. ua/ru/analytics/special-gas/hydrogen utilization, 19 p.

Houa S.S., Chenb C.H., Changb C.Y., Wuc C.W., Ouc J.J., and Linb T.H. (2011) Firing blast furnace gas without support fuel in steel mill boilers. *Energy Conversion and Management*, vol. **52**, No.7, pp. 2758–2767.

John J. (2002) *New Technologies and Alternative Fuels*. McMullen Associates, Inc. with Booz Allen Hamilton. – May 2, 2002 (5/2/02), 67 p. (with Appendixes A,B,C,D,E,F)

Kondepudi D. and Prigogine I. (1999) Modern *Thermodynamics: from Heat Engines to Dissipative Structures*. New York/Weinheim/Brisbone/Toronto/Singapore, Wiley, Chichester, 380 pp.

Liss W. (2012) Demand Outlook: A Golden Age of Natural Gas. *CEP Magazine*, august 2012, pp. 35 – 40.

Marx G. (2010) Das Energiekonzept der Bundes regierung-Einstieg in eine Energie-effizienzpolitik? // *GasWärme Int.* 2010(59), Nr.7-8. – S. 541–543

(NGPO) Natural Gas Price outlook. (2009) Energy Solutions: natural gas buying advisors, March. – pp. 1–9.

Ptasinski K.J., Prins, M.J., and Pierik A. (2006) Exergetic evaluation of biomass gasification. Energy doi: 10.1016/J. energy.2006.06.024, 7 p.

Soroka B.S. (1993) *Intensification of Thermal Processes in Fuel Furnaces*. Kiev, Naukova Dumka Publishing House, 413 p. (In Russian).

Soroka B. and Sandor P. (2000) Combined power and environmental optimization of the fuel type by reheating and thermal treatment processes. *Proc. of the 21st World Gas Conference*, 6-9 June 2000, Nice, France, 15 p.

Soroka B.S. (2009) Definition of main combustion characteristics of gas mixtures. Part 1. Physical fundamentals of modern models of the flame front formation. *Power Technologies and Resources Saving*, **5**, pp. 23–30.

Soroka, B.S. (2010) Utilization of alternative gases with the purpose of natural gas saving by heating of high – temperature plants. *Renewable Energetics*, no. **1** (20), pp.5–17. (in Russian)

Soroka B. (HiTACG) (2010) Development of scientific and engineering fundamentals of hydrocarbons (natural gas) substitution for alternative gases. *Proc. of 8th International Symposium on high temperature air combustion and gasification* (*HiTACG*), 5–7 July Poznan, Poland, pp. 275–283.

Vestenberg P., Niehoff T., and Paul R. (2007) Solutions for growth – Oxyfuel meets new melting and heating demands. *Heat Processing*, vol. **5**, No.2, pp.152–155.

Warnatz J., Maas U., and Dibble R.W. (2001) *Combustion: Physical and chemical Fundamentals*, *Modelling and Simulations*, *Experiments*, *Pollutant Formation*. Springer, 299 p.

Weber E.J. (1966) *Interchangeability of Fuel Gases*. Gas Engineering Handbook. Fuel Gas Engineering Practices/First Edition, Second Printing. Section 12, Chapter 14, N. Y. The Industrial Press, pp. 12/239 – 12/252.

White D.L. (1966) *Gas Calorimetry*. Gas Engineering Handbook. Fuel Gas Engineering Practices/First Edition, Second Printing. Section 6, Chapter 8, N. Y. The Industrial Press, pp. 6/42 – 6/47.