Топливо и энергетика

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The Fuel Certification by Heat Engineering Characteristics

Methodology of the fuels certification by consideration the last as the commodity products has been composed basing on option of the main power characteristics and on statement of their compliance with the values regulated by the standards. The most significant fuel parameters that evaluate the fuel's suitability for use in specific combustion plants were selected. High and low combustion heat values, along with the theoretical combustion temperature have been proposed as the main heat engineering parameters for the fuels evaluation. The Wobbe indices, high and low, are considered as well among the fuel characteristics to be estimated.Calculations of the calorific values by the original author's techniques for a range of fuels, including alternative fuel gases and the gas mixtures — analogs of the natural gases produced from different gas fields, were performed. The author's calculated results of main heat engineering parameters of fuels were compared with the data obtained by measurements and calculations, tabulated in reference books of foreign sources. It has been established that the relative divergences for mentioned values have a minimum difference (less than 1 %). The calculated dependencies for definition the flow rates of the low and high calorific fuels based on accounting the differences between the total enthalpies of the air-fuel mixture and combustion products of appropriate fuels are presented. A method of forming the price on consumable fuel has been proposed taking into account the different cost of 1 MJ of the energy for various fuels under consideration. *Bibl. 11, Fig. 5, Table 6.*

Key words: alternative gas fuels, certification, fuel cost, high and low calorific value, theoretical combustion temperature, total enthalpy, Wobbe number.

Introduction

Fuel certification makes one of the most important stages by determination of optimal fuel type in the framework of the fuel consideration as a commodity product. The procedure is performed in accordance with requirements for fuels use and to the plants where fuel is burnt. Estimation of the possibilities of implementation the plant with chosen fuel firing is carried out, under accounting the specifics of thermal plant and the modes of operation the last.

Taking into consideration the set of the fuel characteristics being attributive for certification of these products, the thermal and flame characteristics of fuels should be defined including the following parameters: higher Q_h and lower Q_l calorific value; higher Wo_h and lower Wo_l Wobbe numbers; theoretical combustion temperature T_T, absolute density ρ and density d relative to the air, volumetric L_{st} and mass Ω_{st} stoichiometric numbers, methane number MZ, ignition T_{ig} and flash T_{flash} temperatures, normal flame spread velocity u_n (S_L), flame spread limits (lower and higher by the percentage content of fuel in fuel-oxidant mixture or by coefficient of oxidant excess) [1].

Option of appropriate type of fuels for firing the power, industrial or heating plants in frame of modern approaches is mainly defined by combination offset of conditions: process, fuels accessibility and price as well as of environmental limitations.

That's why by decision the problem of supplying the appliances with optimal type of fuel from environmental standpoint, various primary energy sources are to be taken into account including fossil fuels and nuclear sources.

Particularly in USA the trend has appeared to preserve old nuclear reactors whose economic viability is threatened by cheap natural gas and rising production of wind energy.

The last sources of electricity provide an opportunity to operate with little or no production of greenhouse gases to effect the climate. The loss of zero-carbon emission nuclear plants from the electricity grid would likely lead to millions of tons of additional carbon dioxide in the atmosphere each year, because the substitute would be fossil fuels [2].

1. Option of techniques to predict the fuels' thermal characteristics

1.1. Theoretical (adiabatic) combustion temperature. The most representative of mentioned parameters for fuels make the combustion temperatures and the calorific values.

Dependence of the theoretical combustion temperature T_T for different fuels on type of higher hydrocarbons C_nH_{2n+2} in mixture with an air (in dependence of fuel composition — on number of carbon atoms n) is presented in Fig. 1. An air — oxidant is considered in two states: completely dry air and an air, saturated with water vapor. The computations have been performed by using the CANTERA computer code. Conditions of computations are given under the picture.

Observation the Fig. 1 shows that growth of T_T with increasing of n is retarded after transition from the lightest gas of the alkanes — beginning from methane. Air humidification reduces T_T values, but curves of dependence for both compared oxidants are congruent (similar).

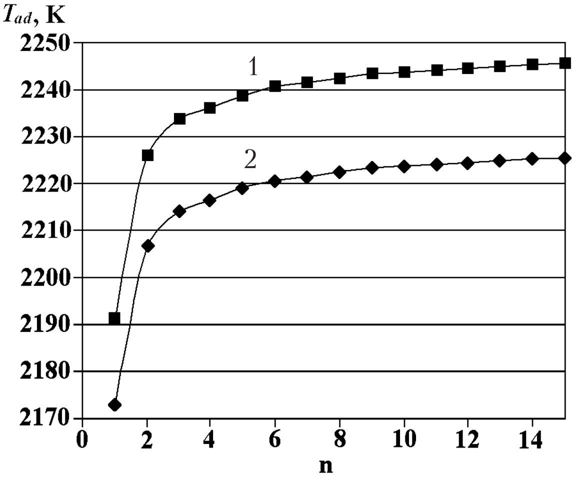

Fig. 1. Theoretical combustion temperature $T_T = T_{ad}$ of air mixtures of n-alkanes C_nH_{2n+2} (in dependence of number of carbon atoms): 1 — dry air; 2 — wet air, H_2O vapour content d = 24.4 g H_2O/kg dry air. Fuel-oxidant mixture temperature 300 K, air excess factor λ = 1.05.

Dependence of adiabatic (approximated to the theoretical) combustion temperature on Equivalence Ratio ER = λ^{-1} — value, inverse to the air excess factor (coefficient) λ — is presented in Fig. 2 for two types of heavy hydrocarbon fuels. The data for heptane C_7H_{16} and octane C_8H_{18} at λ = 1.05 are strongly correlated with the theoretical combustion temperature for the specified fuels (Fig.1) by condition of option the same λ value at compared figures.

In Table 1 the compositions and theoretical combustion temperatures T_T of 30 types gas fuels have been generalized. These fuels are studying below in this paper from the standpoint of determination their individual thermal characteristics.

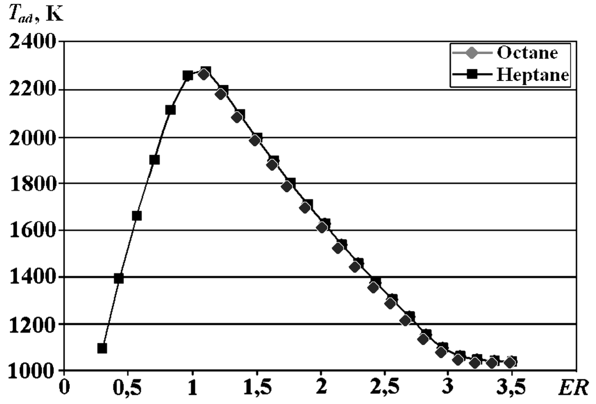

Fig. 2. Adiabatic combustion temperature of an air mixtures with heptane and with octane in dependence of the Equivalence Ratio ER = λ^{-1}.

By this calculations T_T values are computed by two approaches following from results of using two various cades: «FUEL» (denoted as «F») and «TERRA» (denoted as «T»). The short description of both computer codes is given below.

1.2. Combustion heat (calorific) values. As for the calorific values, significant cycle of calculations was carried out according to the method described in our report in frame of the project T01 STCU-NASU # 5722.

Both of the calculated values Q_l and Q_h – refers to the standard temperature T_0 = 298 K. Lower calorific value (low (net) heat value) Q_l is determined by extrapolation the results of calculations of the equilibrium reaction heat, taken at temperatures $T \geq 373$ K (absence of H_2O in the liquid water form) to the standard temperature T_0 = 298 K. Higher calorific value (high (gross) heat value) Q_h was calculated by adding the heat of evaporation $\Delta Q_{ev,eq,To}$ to the equilibrium calorific value $Q_{eq,To}$ of the equilibrium wa-

Table 1. The initial fuels composition and theoretical combustion temperature T_T of an air stoichiometric mixture with fuel gases considered below in the paper

Numbers	Gas fuel	Composition in mol. %											T_T	
		CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_6H_{14}	H_2	N_2	CO_2	CO	O_2	T	F
1	CH_4	100	–	–	–	–	–	–	–	–	–	–	2227	2221
2	C_2H_6	–	100	–	–	–	–	–	–	–	–	–	2262	2255
3	C_3H_8	–	–	100	–	–	–	–	–	–	–	–	2269	–
4	C_4H_{10}	–	–	–	100	–	–	–	–	–	–	–	2272	–
5	C_5H_{12}	–	–	–	–	100	–	–	–	–	–	–	2274	–
6	C_6H_{14}	–	–	–	–	–	100	–	–	–	–	–	2276	–
7	Nordsee-Erdgas H	86.22	8.61	1.91	0.39	0.05	0.02	–	0.90	1.90	–	–	2230	2222
8	Misch-Erdgas H	87.43	6.85	0.92	0.16	0.02	0.01	–	2.64	1.97	–	–	2226	2219
9	Russ-Erdgas H	97.61	1.01	0.33	0.11	0.01	0.01	–	0.83	0.09	–	–	2228	2220
10	Holland-Erdgas L	83.04	4.00	0.82	0.22	0.06	0.05	–	10.09	1.72	–	–	2217	2209
11	Verbund-Erdgas L	85.43	2.93	0.48	0.15	0.03	0.04	–	9.19	1.75	–	–	2216	2209
12	Weser-Erdgas L	88.08	0.61	0.04	0.02	–	–	–	8.69	2.56	–	–	2212	2205
13	H-Gas Ref._GWI	90.31	5.46	1.19	0.32	0.07	0.04	–	1.17	1.43	–	–	2229	2221
14	H-Gas 3_GWI	67.74	4.09	15.64	0.24	0.05	0.03	10.00	1.13	1.07	–	–	2244	2233
15	H-Gas 1_GWI	74.96	4.53	0.99	0.27	0.06	0.03	15.30	0.97	2.89	–	–	2232	2224
16	H-Gas Ref._DBI	98.04	0.82	0.24	0.08	0.01	< 0.01	–	0.77	0.03	–	–	2227	2220
17	H-Gas 3_DBI	69.02	0.58	17.87	0.06	0.01	< 0.01	9.45	2.99	0.02	–	–	2244	2232
18	H-Gas 1_DBI	82.01	0.69	2.00	0.07	0.01	< 0.01	9.0	6.00	0.03	–	–	2228	2220
19	Natural gas	99.00	–	–	–	–	–	–	0.80	0.20	–	–	2226	2219
20	Sewage gas	35.00	–	–	–	–	–	–	10.00	55.00	–	–	1939	1932
21	Lean gas from REW product gas	12.00	–	–	–	–	–	25.00	3.00	25.00	35.00	–	2166	2160
22	Landfill gas	30.00	–	–	–	–	–	–	70.00	–	–	–	1995	1989
23	Mine gas	25.00	–	–	–	–	–	–	65.00	10.00	–	–	1910	1903
24	Gas from biomass	5.00	–	–	–	–	–	15.00	50.00	10.00	20.00	–	1937	1931
25	Wood gas	5.00	–	–	–	–	–	15.00	50.00	15.00	15.00	–	1842	1836
26	50 % by weight chicken manure / 50 % by weight wood chips	13.60	–	–	–	–	–	31.40	4.50	27.60	22.30	0.60	2138	2135
27	Pure beech wood chips	14.72	–	–	–	–	–	25.22	4.02	29.53	23.84	2.67	2150	2149
28	30% by weight oat husks / 70 % by weight wood chips	20.00	–	–	–	–	–	24.59	11.62	23.33	20.09	0.36	2133	2131
29	100 % by weight digestate	10.30	–	–	–	–	–	30.40	10.00	25.30	23.80	0.20	2118	2117
30	100 % by weight mill scale sludge	5.50	–	–	–	–	–	24.10	40.30	14.80	14.80	0.50	1974	1973

Notes: 1. The data by the components' fraction in the Table are conditionally presented as rounded values with two fixed number signs after the point. Indeed the numerical procedures have been performed with values of 4 signs after the point. 2. Initial temperatures of fuel gas and air-oxidant are taken of standard value: T_0 = 298 K, p_0 = 101.325 kPa ter (liquid phase) fraction of combustion products at T_0 = 298 K. Another approach makes an addition of evaporation heat $\Delta Q_{ev,\sum,To}$ for total H_2O amount contained in the combustion products to the net calorific value Q_l:

$$Q_h = Q_{eq,To} + \Delta Q_{ev,eq,To}; \quad (1)$$

$$Q_h = Q_l + \Delta Q_{ev,\sum,To}. \quad (2)$$

Results of our calculations and comparison of Q_l and Q_h values according to our calculations and the data given in the literature are summarized in Tables 2–4.

Our computation were carried out using original computer code «FUEL», developed under the direction of prof. B. S. Soroka at the Gas Institute of NASU (marked with the letter «F» in these tables) [4] and computer code «TERRA», developed at N. E. Bauman Moscow State Technical University (Russia) under the direction of prof. B. G. Trusov [5] (marked with the letter «T» in these tables).

In Table 2 are compared our calculations of Q_l, Q_h values for higher hydrocarbons C_1–C_6 with data from the DIN EN ISO 6976 [3]. The computed values have the minimum relative deviation of relevant referred (< 0,5 %).

The next step made comparison of our results with data by the GasWarme Institute, Essen (Germany), summarized in [6]. In Table 3 are collected the data those meet to six (6) different types of natural gases (H, L) each of specific composition. These fuels are delivering from various sources of production and supply. In addition this table contains data for six gas mixtures offered by German institutes GWI and DBI as the fuels similar to the natural gases of various origins. Gases-analogs are proposed from the standpoint of restrictions under provision of calorific values and the Wobbe numbers, regulated by German standards G 260.

For the listed gas fuels, including examples concerning partial addition of propane and hydrogen, the relative deviation the values of Q_l and Q_h is not exceed 0.75 % (see Table 3).

In the next Table 4 the calorific values Q_l and Q_h are compared for a wide range of alternative fuels: gasification products (synthesis gases), gases of biological origin, landfill gases, etc.

In the last Table 4 coincidence of the data being compared is quite satisfactory (relative divergence ≈ 1 %), excepting the cases, where authors from the GasWarme Institut (GWI) made mistakes and have obtained the results erroneous in our opinion. This statement is grounded upon evaluation of our data adequacy and of falsity of the referred calculations [3] that is recognized by GWI's authors of the cited paper by our direct discussion with them. All the combustion heat data both original (subscript «or») and referred (subscript «ref») — were compared by equation:

$$\delta Q = (Q_{ref}/Q_{or} - 1) \cdot 100 \% \quad (3)$$

and were given within respective columns in the Tables 2–4.

Table 2. Comparison of calorific values Q_l and Q_h for n-alkanes C_nH_{2n+2}

Numbers	Fuel	Calorific value	Our computations		References [3]		Relative divergence, δQ, %
			kJ/m³	kWh/m³	kJ/m³	kWh/m³	
1	CH_4	Q_h	T 39 699.67	11.03	39735	11.04	0.09
			F 39 568.76	10.99			0.42
		Q_l	T 35 794.65	9.94	35808	9.95	0.04
			F 35 636.97	9.90			0.48
2	C_2H_6	Q_h	T 69 589.35	19.33	69630	19.34	0.06
			F 69 361.56	19.27			0.39
		Q_l	T 63 729.78	17.70	63740	17.71	0.02
			F 63 469.21	17.63			0.42
3	C_3H_8	Q_h	T 99 016.76	27.50	99010	27.50	−0.01
		Q_l	91 203.04	25.33	91150	25.32	−0.06
4	C_4H_{10}	Q_h	T 128 353.54	35.65	128370	35.66	0.01
		Q_l	118 585.71	32.94	118560	32.93	−0.02
5	C_5H_{12}	Q_h	T 157 745.69	43.82	157750	43.82	0.00
		Q_l	146 023.89	40.56	145960	40.54	−0.04
6	C_6H_{14}	Q_h	T 187 137.30	51.98	187160	51.99	0.01
		Q_l	173 461.51	48.18	173410	48.17	−0.03

Table 3. Comparison of calorific values Q_l and Q_h for natural gases of different gas-field origin (sources) (1–6) and gases-analogs (7–12)

Numbers	Fuel	Calorific value	Our computations			References [3]		Relative divergence, δQ, %
				kJ/m^3	kWh/m^3	kJ/m^3	kWh/m^3	
1	Nordsee-Erdgas H	Q_h	T	42 726.33	11.87	42 858.00	11.91	0.31
			F	42 655.38	11.85			0.47
		Q_l	T	38 659.20	10.74	38 757.60	10.77	0.25
			F	38 532.15	10.70			0.58
2	Misch-Erdgas H	Q_h	T	40 646.49	11.29	40 795.20	11.33	0.36
			F	40 535.35	11.26			0.64
		Q_l	T	36 739.46	10.21	36 853.20	10.24	0.31
			F	36 589.23	10.16			0.72
3	Russ-Erdgas H	Q_h	T	39 955.16	11.10	40 086.00	11.14	0.33
			F	39 836.79	11.07			0.62
		Q_l	T	36 045.26	10.01	36 144.00	10.04	0.27
			F	35 891.75	9.97			0.70
4	Holland-Erdgas L	Q_h	T	37 035.19	10.29	37 159.20	10.32	0.33
			F	36 942.09	10.26			0.58
		Q_l	T	33 458.47	9.29	33 552.00	9.32	0.28
			F	33 325.31	9.26			0.68
5	Verbund-Erdgas L	Q_h	T	36 750.81	10.21	36 867.60	10.24	0.32
			F	36 646.00	10.18			0.60
		Q_l	T	33 181.49	9.22	33 267.60	9.24	0.26
			F	33 042.13	9.18			0.68
6	Weser-Erdgas L	Q_h	T	35 456.52	9.85	35 568.00	9.88	0.31
			F	35 341.79	9.82			0.64
		Q_l	T	31 976.27	8.88	32 061.60	8.91	0.27
			F	31 836.14	8.84			0.70
7	H-Gas Ref.GWI	Q_h	T	41 430.75	11.51	41 590.80	11.55	0.38
			F	41 350.58	11.49			0.58
		Q_l	T	37 446.01	10.40	37569.60	10.44	0.33
			F	37 316.49	10.37			0.67
8	H-Gas 3_GWI	Q_h	T	46 943.47	13.04	47 160.00	13.10	0.46
			F	47 149.57	13.10			0.02
		Q_l	T	42 608.62	11.84	42782.40	11.88	0.41
			F	42 631.35	11.84			0.35
9	H-Gas 1_GWI	Q_h	T	36 326.47	10.09	36 446.40	10.12	0.33
			F	36 266.02	10.07			0.49
		Q_l	T	32 721.89	9.09	32810.40	9.11	0.27
			F	32 612.77	9.06			0.60
10	H-Gas Ref._DBI	Q_h	T	39 856.16	11.07	39 996.00	11.11	0.35
			F	39 739.21	11.04			0.64
		Q_l	T	35 951.37	9.99	36072.00	10.02	0.33
			F	35 801.44	9.94			0.75
11	H-Gas 3_DBI	Q_h	T	46 785.62	13.00	47 160.00	13.10	0.79
			F	47 001.32	13.06			0.34
		Q_l	T	42 469.61	11.80	42624.00	11.84	0.36
			F	42 486.02	11.80			0.32
12	H-Gas 1_DBI	Q_h	T	36 290.90	10.08	36 396.00	10.11	0.29
			F	36 227.72	10.06			0.46
		Q_l	T	32 705.02	9.08	32796.00	9.11	0.28
			F	32 591.37	9.05			0.62

Table 4. Comparison of calorific values Q_l and Q_h for natural and alternative gases of different origins

	Fuel	Calorific value	Our computations			References [3]		Relative divergence, δQ, %
				kJ/m^3	kWh/m^3	kJ/m^3	kWh/m^3	
1	Natural gas	Q_h	T	39 303.18	10.92	–	–	–
			F	39 173.68	10.88			
		Q_l	T	35 437.14	9.84	35535.60	9.87	0.28
			F	35 279.90	9.80	35535.60	9.87	0.72
2	Sewage gas	Q_h	T	13 897.15	3.86	–	–	–
			F	13 828.08	3.84			
		Q_l	T	12 530.23	3.48	12585.60	3.50	0.44
			F	12 457.54	3.46	12585.60	3.50	1.02
3	Lean gas from REW product gas	Q_h	T	12 274.46	3.41	–	–	–
			F	12 318.35	3.42			
		Q_l	T	11 324.24	3.15	11239.20	3.12	−0.76
			F	11 360.67	3.16	11239.20	3.12	−1.08
4	Landfill	Q_h	T	11 912.95	3.31	–	–	–
			F	11 884.51	3.30			
		Q_l	T	10 741.58	2.98	10753.20	2.99	0.11
			F	10 704.35	2.97	10753.20	2.99	0.45
5	Mine gas	Q_h	T	9 930.74	2.76	–	–	–
			F	9 900.18	2.75			
		Q_l	T	8 954.33	2.49	8964.00	2.49	0.11
			F	8 918.26	2.48	8964.00	2.49	0.51
6	Gas from biomass	Q_h	T	6 427.66	1.79	–	–	–
			F	6 405.99	1.78			
		Q_l	T	5 939.74	1.65	5936.40	1.65	−0.06
			F	5 916.90	1.64	5936.40	1.65	0.33
7	Wood gas	Q_h	T	5 766.58	1.60	–	–	–
			F	5 774.26	1.60			
		Q_l	T	5 280.71	1.47	5306.40	1.47	0.48
			F	5 285.23	1.47	5306.40	1.47	0.40
8	50 % chicken manure/ 50 % wood chips	Q_h	T	12 304.62	3.42	–	–	–
			F	12 321.10	3.42			
		Q_l	T	11 157.58	3.10	11088.00	3.08	−0.63
			F	11 163.14	3.10	11088.00	3.08	−0.68
9	Pure beech wood chips	Q_h	T	12 733.56	3.54	–	–	–
			F	12 740.26	3.54			
		Q_l	T	11 630.39	3.23	11232.00	3.12	−3.55
			F	11 629.24	3.23	11232.00	3.12	-3.54
10	30 % oat husks /70 % wood chips	Q_h	T	13 506.65	3.75	–	–	–
			F	13 644.81	3.79			
		Q_l	T	12 254.36	3.40	979.00	2.72	−25.15
			F	12 371.82	3.44	9792.00	2.72	−26.35
11	100 % digestate	Q_h	T	10 947.24	3.04	–	–	–
			F	10 973.53	3.05			
		Q_l	T	9 955.34	2.77	13356.00	3.71	25.46
			F	9 971.16	2.77	13356.00	3.71	25.34
12	100 % mill scale sluge	Q_h	T	7 105.62	1.97	–	–	–
			F	7 182.11	2.00			
		Q_l	T	6 423.76	1.78	9756.00	2.71	34.16
			F	6 485.80	1.80	9756.00	2.71	33.52

1.3. Wobbe numbers. If values of Q_l and Q_h refers to 1 Nm^3 of gas fuel, then a thermal power fuel flow can be associated with the common characteristics, which have the same dimension as the calorific values and Wobbe numbers Wo. These indicators are clearly associated with another physical characteristic of the fuel gas — with the gas relatively normal density $\rho_{f,N} / \rho_{a,N}$:

$$Wo_l = Q_l(\rho_{a,N}/\rho_{f,N})^{1/2}; \qquad (4)$$

$$Wo_h = Q_h(\rho_{a,N}/\rho_{f,N})^{1/2}. \qquad (5)$$

Under observance the equations given above the proportionality of Wobbe numbers: lower Wo_l and higher Wo_h — with respective calorific values Q_l and Q_h could be state, In fact, taking into account the simultaneous change the physical and chemical characteristics of the fuels, including varying the density of the gas, proportionality of the Wobbe numbers and corresponding calorific values is revealed only within certain ranges of variation the values of Q_l, Q_h and Wo_l, Wo_h (Fig. 3, Fig. 4).

2. Influence of fuel-oxidant potential on combustible consumption (gas flow rate) and price

2.1. Gas fuel flow rate. Fuel consumption. as already noted could be calculated according to the balance equations [8] for useful heat flux using the difference of the absolute total enthalpies $I_T - I_{fl}$ at T_T and at T_{fl}, or of respective excess enthalpies $\Delta I_T - \Delta I_{fl}$ for mass flow rates of the fuels under consideration:

$$\begin{aligned} Q_{use} &= B_f'(I_{f,T}' - I_{f,fl}') = \\ &= B_f''(I_{f,T}'' - I_{f,fl}'') \end{aligned} \qquad (6)$$

or for heat transfer medium — combustion products (flue gases) related to respective flow rate of fuel mass. In the last case mass flow (consumption) of fuel $\dot{m}_f = B_f$ is replacing by mass flow rate of combustion products (flue gases):

$$\dot{m}_{fl} = (1 + \lambda\,\Omega_{st})\,\dot{m}_f\,, \qquad (7)$$

where $B_f = \dot{m}_f$; $\dot{m}_{fl}$ — mass flow rates of fuel and of combustion products — respectively; Ω_{st} — mass stoichiometric ratio «oxidant : fuel».

It means that excess enthalpy of fuel is determined by excess enthalpy of corresponding mass flow of combustion products.

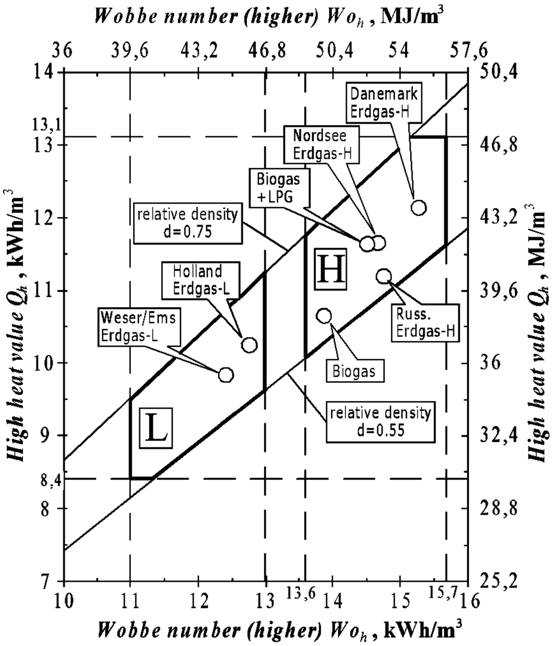

Fig. 3. Range of interdependence of the combustion heat (higher) and Wobbe number (higher) for natural gases of EU widespread groups L and H, with partial addition of data related to biogases and to other fuel mixtures [7].

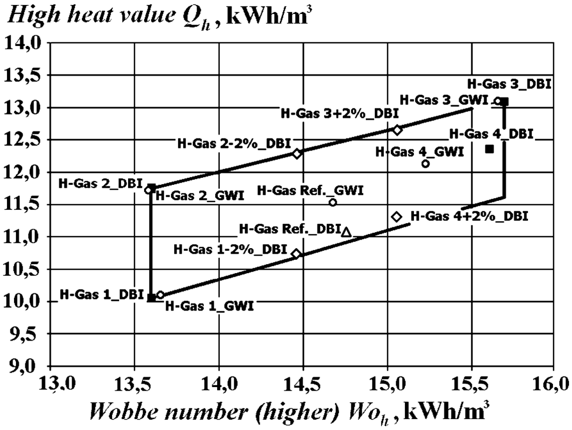

Fig. 4. Range of interdependence of the combustion heat (higher) and Wobbe number (higher) for gas mixtures simulating the natural gases in accordance with the compositions proposed by GWI and DBI [7].

The equation (6) determines value of useful heat in case of the «ideal furnace» and outlet flue gases temperature T_{fl} at the furnace exit for two compared fuels.

Relationship of fuel consumptions: between high calorific fuel with high theoretical combustion temperature (superscript «′») and low calorific fuels with lower theoretical combustion temperature (superscript «″») — is determined according to the heat balance equation (6):

$$\frac{B_f'}{B_f''} = \frac{I_{f,T}'' - I_{f,fl}''}{I_{f,T}' - I_{f,fl}'} = \frac{\Delta I_{f,T}'' - \Delta I_{f,fl}''}{\Delta I_{f,T}' - \Delta I_{f,fl}'} \qquad (8)$$

or

$$\frac{B_f'}{B_f''} = \frac{\Delta I_{f,T}''}{\Delta I_{f,T}'} \frac{1-\Delta I_{f,fl}''/\Delta I_{f,T}''}{1-\Delta I_{f,fl}'/\Delta I_{f,T}'}. \qquad (9)$$

If $\Delta I_{f,T}' > \Delta I_{f,T}''$ and $T_T' > T_T''$, then the following inequality is valid by fixed T_{fl}:

$$\Delta I_{f,fl}' > \Delta I_{f,fl}''. \qquad (10)$$

In particular, in the absence of the combustion components preheating:

$$\frac{B_f'}{B_f''} = \frac{Q_l''}{Q_l'} \cdot \frac{1-\Delta I_{f,fl}''/Q_l''}{1-\Delta I_{f,fl}'/Q_l'} < \frac{Q_l''}{Q_l'}. \qquad (11)$$

The last correlation could be explained as follows: flow rate B_f' of high calorific and high combustion temperature fuel is differed of flow rate B_f'' of low calorific and lower combustion temperature fuel to a greater extent than under simple ratio of the combustion heats (calorific values). The combustion temperature and specific excess of total enthalpy those meet to the fuel-oxidant mixture potential and defined its value, cause an additional effect on B_f.

Comparative researches of influence the fuel potential taken in form of specific excess fuel's total enthalpy ΔI_T up on fuel consumption have been carried out in presentation [9]. Variation in absolute consumption of one of the fuel's components (for example, of natural gas when the last is used jointly with another components in the mixture – the mixed fuel) could be estimated by means of an expression for the relative change of the fuel consumption obtained from the enthalpy balance for the fuel-using plant. Some results on influence the fuel mixture composition on consumption of natural gas being mixed with the process gases have been considered in [9] basing on thermodynamic background. Not each of the alternative fuels could be used for the steel preheating because this process is related to the high-temperature treatment operation. An opportunities of reduction the natural gas (NG) consumption in the mixture with the process gases is limited in case of low-calorific gases (blast-furnace gas BFG for example) by comparatively low operation temperature — below T_{fur}= 1450 K.

Any heat (enthalpy) saving is not observed in comparison with clean NG application for the case of BFG — NG mixture combustion due to admix the BFG to NG within temperature range $T_{fur} \in \{800\ \mathrm{K};\ 1600\ \mathrm{K}\}$. Continuous over-expenditure of required heat is marked within indicated conditions.

In case of high-temperature coke-oven gas combustion jointly with the natural gas, the NG saving as well as the required heat (enthalpy) reduction would be fixed by any furnace process temperature $T_{fur} \in \{800\ \mathrm{K};\ 2200\ \mathrm{K}\}$.

In frame of present researches mentioned above an additional influence of share of natural gas in mixture with coke-oven gas on change the relative fuel consumption (by fuel's heat) is shown in Fig. 5 in dependence on variation the temperature conditions of furnace operation.

Because of coke-oven gas (COG) has greater T_T than respective values T_T for NG, any operation with mixture of both fuel gases is accompanied with increase of fuel rate in comparison with application of clean COG (when

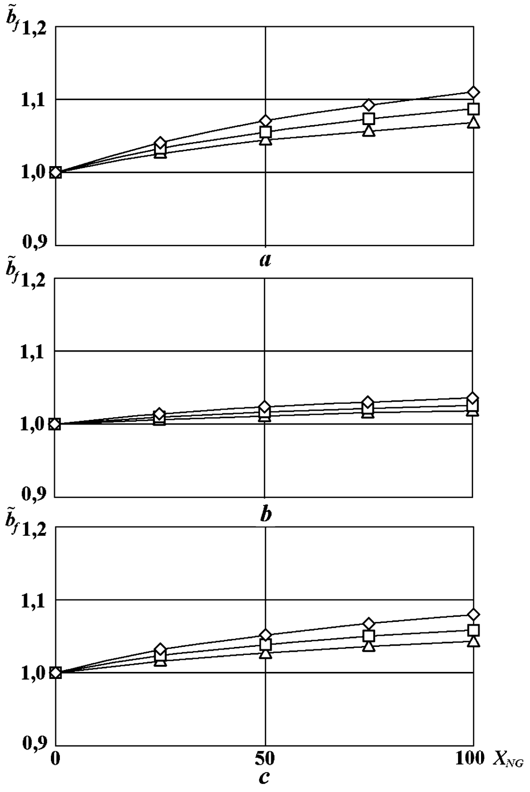

Fig. 5. Relative fuel's heat consumption $\tilde{b}_f$ in dependence on natural gas share X_{NG}, % vol, in the combustible mixture with coke-oven gas.Combustion air preheating temperature T_{air} = 600 K. Flue gases temperature at the furnace exit T_{fl}, K: 1 — 1473; 2 — 1573; 3 — 1673. Air excess factor λ: a — 0.8; b — 1.0; c — 1.25. Thermodynamically ideal furnace.

Table 5. Prices for natural gas (NG) accordingly data by National Joint-Stock Company «Naftogas of Ukraine» [10]

Cost characteristics	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Price for supplying the NG, USD/1000 m^3	50	95	130	179.5	228.8	259.7	309	420.3	396	428.8*
Price of NG for consumers, UAH/1000 m^3	327.3	417	708	1680	2020	2880	3382	3509	3420	4724

Note: * — accordingly IMF's prognosis.

$X_{NG} = 0$) — see relative specific fuel consumptions in dependence on X_{NG} — Fig. 5.

For all that to determine the fuel utilization efficiency in the furnace efficiency could be used that is attributed to the higher or to the lower calorific value, respectively:

$$\eta_{f,h} = Q_{use}/(B_f \cdot Q_h); \qquad (12)$$

$$\eta_{f,l} = Q_{use}/(B_f \cdot Q_l). \qquad (13)$$

The enhanced values of efficiencies on fuel and on heat utilization make the reason of reduction the fuel and heat flow rates in case of high potential fuel application [9].

2.2. Payment for consumed fuel gas. It is accepted in Ukraine and countries of former Soviet Union until present to perform domestic and international settlements with the consumers for gas fuel (natural gas) supply basing upon the volume of delivering fuel and on the contract price for each 1000 m^3 of natural gas (NG). Meanwhile the composition and heat engineering characteristics of the fuels, those are changed continuously, do not taken into account.

The prices assigned for 1000 m^3 of natural gas are not objective but conditional values being in higher degree depended on political conjuncture. For example in Table 5 are given the prices for delivering of 1000 m^3 of natural gas (NG).

It's obvious that increase of prices by 8 times and more during mentioned period could not be well-founded. This change greatly exceeds relative lowering the NG prices in USA due shale gas revolution and huge enhancement of the hydrocarbons market in America — respectively.

In our opinion fixation of the prices for 1 MJ of definite fuels in combination with account of the fuel flow rates delivering seems to make more valid approach for solution the problem of adequate fuels price formation.

In this connection, by proceeding the certification of the gas fuels and by fixing of their prices for consumers two factors are proposed to be considered: 1) type of fuel; 2) price of 1 MJ of combustion heat for the selected fuels.

These factors should be considered by means of account the different cost of the fuels preparation by transportation (refining, liquefaction, etc.), cost of transportation itself (because of corresponding specific volumes of gases — according to calorific value), and of different energy consumption with draught devices for obtaining 1 MJ of thermal energy.

According to the data (Table 6) cost of 1 MJ of energy makes constant value for any type of natural gases, which causes the different price for 1 m^3 (or, as it is adopted — to settle the cost of 1000 Nm^3 or under book — keeping) for various wide-spread natural gases (NG). Because combustion heat for NG of 6 types of European gases H and L [7], which are considered in the German handbooks and inquiry materials have difference in the calorific value (both net Q_l and gross Q_h) in range of 1.2 times between various types of gases, it means more than 20 % difference between the cost of separate natural gases in Europe.

Thus in frame of the row of European natural gases which are distinguished ± 10.45 % by net calorific value comparing the averaged price, last value for NG as a fuel could be differed from 192.37 USD/1000 m^3 to 232.54 USD/1000 m^3 basing upon data given in the Tables 3 and 6, indicated figures could not be taken as a ground for payment and as a true values for any country and consumer in any time. These data represent the evaluation of mentioned approach to determine the fuel price.

Table 6. Cost of 1 MJ of energy in dependence on the fuel type [11]

Fuel	Cost, USD/1 MJ
Liquid natural gas (LNG)	0.006
Compressed Natural Gas	0.006
Propane	0.008
Petrol	0.015
Diesel	0.020

It should be taken into consideration by determining the cost of fuel when calculations are made through the price of 1 MJ, which energy assessment is referred to: of lower Q_l, of higher Q_h or of actual calorific value and if chosen value is referred to standard temperature (298 K). Assumed that $Q_l / Q_h \approx$ idem $\approx 0.9024 \pm 0.001$ [7] determination the absolute cost of the natural gas should be specified of what type of MJ it's concerned.

On the other hand, it should be noted that talking about three different types of combustion heat is related only to the hydrogen-containing fuels, and in particular are suitable for hydrocarbons, including mixtures thereof in natural gas. Generally, calculation of the fuel needs (fuel flow rate) in Ukraine and some other countries the former Soviet Union are performed with Q_l (meets to «Heizwert» $H_{i.n}$ (Germany) [7]) unlike the U.S. where often the characteristic of the fuel energy value is presented in form of Q_h (meets to German «Brennwert» $H_{s.n}$).

Conclusion

It has been proposed the set of criteria to determine the alternative and low-calorific gas fuels by analogy with those been used by natural gases certification in European Union. The following groups of the fuels' characteristics (both heat — and firing engineering) are included into number of special properties of the combustion products, equilibrium compositions, thermodynamic and thermal physics properties of the products in dependence on temperature. Particularly the fuels are characterized by with following parameters: higher Q_h and lower Q_l combustion heat, higher Wo_h and lower Wo_l Wobbe numbers, theoretical (adiabatic) combustion temperature T_T, density ρ and relative density d to an air, volume Lst and mass Ω_{st} stoichiometric ratio methane number MZ, ignition temperature T_{ig}, flash temperature T_{flash}, flame velocity (laminar flame burning velocity) u_n (S_L), limits of flame propagation, lower and higher (fuel % in the mixture with oxidizer or oxidant excess ratio). The calculations of mentioned characteristics for alternative fuels are carried out.

In the framework of this substep the calculation of the flow rates (consumptions) of alternative gases was carried out by varying the potential — excess specific enthalpy and the combustion temperature of fuel-oxidant mixtures — due change of composition the combustion components: an air and fuel gas and under different preheating conditions for an air-oxidizer.

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Сертифікація палива за теплотехнічними характеристиками

Запропонована методологія сертифікації палив як товарного продукту, основана на виборі базових енергетичних характеристик і оцінці їх відповідності значенням, регламентованим нормативами. Виділені найбільш значущі параметри, котрі дозволяють оцінити придатність палива для використання в конкретних вогнетехнічних агрегатах. В якості основних теплотехнічних параметрів при оцінці палив запропоновані вища та нижча теплоти згоряння, а також теоретична температура горіння. У числі оцінюваних характеристик палив розглядаються також числа Воббе, вище та нижче. Проведені розрахунки теплот згоряння по оригінальним методикам для ряду палив, включаючи альтернативні паливні гази і газові суміші — аналоги природних газів різних газових родовищ. Отримані результати розрахунків авторів співставлялись з даними закордонних вимірювань, а також розрахунків, табульованих в довідкових виданнях. Встановлено, що відносне розходження згаданих величин має мінімальне значення (менше 1 %). Представлено розрахункові залежності для оцінки співвідношення витрат низько- та висококалорійних палив на основі врахування різниці повних ентальпій паливо-повітряної суміші і продуктів згоряння порівнюваних палив. Запропонована методика ціноутворення споживаного палива, яка враховує різну вартість 1 МДж енергії відповідного палива. *Бібл. 11, рис. 5, табл. 6.*

Ключові слова: альтернативні газові палива, вартість палива, вища і нижча теплота згоряння, повна ентальпія, сертифікація, теоретична температура горіння, число Воббе.

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Сертификация топлива по теплотехническим характеристикам

Предложена методология сертификации топлив как товарного продукта, основанная на выборе базовых энергетических характеристик и оценке их соответствия значениям, регламентируемым нормативами. Выделены наиболее значимые параметры, которые позволяют оценить пригодность топлив для использования в конкретных огнетехнических агрегатах. В качестве основных теплотехнических параметров при оценке топлив предложены высшая и низшая теплоты сгорания, а также теоретическая температура горения. В числе оцениваемых характеристик топлив рассматриваются также числа Воббе, высшее и низшее. Проведены расчеты теплот сгорания по оригинальным авторским методикам для ряда топлив, включая альтернативные топливные газы и газовые смеси — аналоги природных газов различных месторождений. Полученные результаты расчетов авторов сопоставлялись с данными зарубежных измерений, а также расчетов, табулированных в справочных изданиях. Установлено, что относительные расхождения упомянутых величин имеют минимальные значения (менее 1%). Представлены расчетные зависимости для оценки соотношения расходов низко- и высококалорийных топлив на основе учета разности полных энтальпий топливо-воздушной смеси и продуктов сгорания сравниваемых топлив. Предложена методика ценообразования потребляемого топлива, учитывающая различную стоимость 1 МДж энергии соответствующего топлива. *Библ. 11, рис. 5, табл. 6.*

Ключевые слова: альтернативные газовые топлива, высшая и низшая теплота сгорания, полная энтальпия, сертификация, стоимость топлива, теоретическая температура сгорания, число Воббе.