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Research on the efficiency of hydrogen combustion, alternative and natural non-interchangeable gases

Abstract. The results of determining the gas interchangeability criterion are presented. An analysis of the possibility of adapting existing gas combustion plants for the effective and stable use of a wide range of combustible gases is performed. It is shown that even natural gases from different deposits are not always interchangeable. Recommendations are developed that allow the use of even non-interchangeable gases on the same gas combustion equipment by changing the operating settings or slightly changing the design characteristics of the equipment. The results of the study of heat transfer in the combustion space when the composition of combustible gases changes and the associated changes in the emissivity of combustion products are presented. Recommendations are given on the organization of the combustion process of non-interchangeable gases, including by creating mixtures of combustible gases with the provision of the necessary interchangeability criteria. The purpose of the work is to study the possibility of effective combustion of alternative types of artificial and synthetic combustible gases, including hydrogen, as well as non-interchangeable natural gases in existing gas combustion equipment. Study of the properties of combustible gases characteristic of gas distribution systems of Ukraine, and their compliance with the interchangeability criteria and gas combustion equipment manufactured and supplied for industrial and municipal purposes. The relevance of the issues of ensuring the interchangeability of gases is confirmed by the implementation of regulatory legal acts on the quality indicators of combustible gases and the efficiency of their use in the national legislation of Ukraine. The results of the study provide the possibility of a barrier-free gradual introduction of alternative types of gases and a gradual transition to the combustion of gases with hydrogen content without cardinal changes in the design of existing burners and their operating modes. *Bibl. 26, Fig. 2, Tab. 5.*

Keywords: combustible natural and alternative gases, interchangeability criteria, physico-chemical and combustible properties of gases, efficiency and stability of the use of combustible gases.

Introduction

Today is characterized by an increase in the range and volume of use of alternative artificial and synthetic types of combustible gases.

Changing the composition and physicochemical properties of combustible gases invariably leads to changes in the operating parameters of gas burners and furnaces, as well as their design. If these concepts are neglected and appropriate changes are not made to the operating parameters of the equipment, all important characteristics of fuel efficiency will inevitably change [1–3]. These include:

- fuel efficiency and efficiency coefficient of gas-using equipment;
- excess air coefficient for the burner;
- thermal power of the fuel combustion plant;
- stability of the burner operation in relation to such dangerous phenomena of the combustion process as flame separation and flashback;
- completeness of fuel combustion and the formation of chemical unburned products, soot and other harmful components of combustion products;
- heat transfer from the flare to the heat exchange surfaces of the equipment and the value of the heat output of the installation.

The question of interchangeability is also relevant for natural gases. They are obtained in deposits of different origin. The composition of such gases, their heat of combustion and other characteristics differ significantly. In addition, there is liquefied natural gas (LNG) [4]. The introduction of alternative and unconventional types of gases is relevant, such as shale gas, biogas, generator gases, oil refinery combustible gases, combustible gases obtained from landfills [5–7]. Of particular importance from the point of view of decarbonization are artificial gases using hydrogen [8–11]. And each of them has individual and often sharply different physicochemical characteristics.

Manufacturers of all types of artificial and alternative types of combustible gases set themselves the main goal of producing such gas and obtaining permission to supply it to the gas transportation system. At the same time, as a rule, the issue of the quality of such combustible gas and the acceptability of its composition for existing gas-burning equipment and gas burners produced by the industry remains unconsidered.

Under such conditions, the main thing is neglected – the requirements for the need to ensure high efficiency and environmental safety at the

stage of heat generation. Because sooner or later all these alternative gases will enter the gas distribution network and the burners of gas-burning equipment. Such equipment is designed for a certain, strictly limited composition of the fuel and is configured for certain operating conditions. An arbitrary change in the composition and combustible properties of the gas threatens to change the thermal power of the equipment that uses heat, loss of combustion stability in the form of flame separation or flashback, the appearance of chemical underburning and a decrease in efficiency. Thus, the transition of gas-burning devices to new types of combustible gases requires adaptation of the transportation system, preparation of gases for combustion and the gas-burning devices themselves. The costs of such reconstruction can be significant, and the issue of using alternative types of gases becomes an optimization issue. On the one hand, there are advantages to diversifying combustible gases, and on the other, there are additional costs for adapting the supply system, efficient and stable combustion of such gases.

This raises the question of the practical possibility of interchangeability of different gases and the possibility of their use in the same gas-burning equipment supplied to the market.

Consideration of gas interchangeability issues makes it possible to implement low-cost partial and gradual decarbonization in the area of using gas fuel as an intermediate stage in the transition to more widespread hydrogen combustion.

Methodology

Under interchangeability according to the requirements of the standards [12–15] is understood the possibility of stable, efficient and safe operation of gas-burning equipment when replacing one combustible gas with another without making any changes to the design of the burner and other equipment of the installation that uses the fuel, as well as without changing the operating mode and settings of such equipment.

Therefore, only for interchangeable gases is there a possibility of a smooth and multiple transition in time from one combustible gas, or a mixture of gases, to another combustible gas with the preservation (or minor permissible changes) of the main characteristics of the combustion process. The subject of the study is the problem of stable and efficient use of a wide range of combustible gases

in equipment that is manufactured or supplied for the use of one type of combustible gas. As survey methods, the authors chose an analysis of current regulatory sources implemented in Ukraine, analytical studies in the field of determining the physicochemical properties and interchangeability criteria of combustible gases, experimental and theoretical own research aimed at developing recommendations for the effective and sustainable use of a wide class of available combustible gases.

Results and their discussion

Each country is characterized by a certain permitted range of combustible gases. However, given the global nature of the modern economy and the possibility of using gas equipment from popular and recognized international manufacturers, the issue of interchangeability of combustible gases becomes universal. Significant challenges also arise for manufacturers of gas equipment in terms of the possibility of its effective use for different gases.

According to the requirements of modern standards that have come into force in most European countries [12, 13], all types of combustible gases are divided into categories (families) and groups. The most common second family of gases is divided into three groups according to the interchangeability criterion responsible for maintaining the thermal capacity of the installation when switching from one gas to another.

Table 1 presents the classification of combustible gases of the second family of groups H, L, and E by the value of the simple Wobbe index and provides the limit values of the Wobbe number according to the requirements of DSTU GOST EN 437:2018.

The identity of the Wobbe index $W_1 = W_2$ for two gases means that gas appliances that use different combustible gases will operate with the same thermal power when burning these gases without

any changes in the design of gas burners and furnaces (at the same gas pressure).

The Wobbe index is determined according to the dependence [14]:

$$W_i = \frac{H_i}{\sqrt{d}} = \frac{H_i}{\sqrt{\rho_g / \rho_{air}}}, \quad (1)$$

where H_i – higher heat of combustion of combustible gas, MJ/m³; d – relative density of combustible gas; ρ_g , ρ_{air} – density of combustible gas and air for combustion under the same conditions, kg/m³.

At the regulatory level in Ukraine, it is important to determine the permissible values of the ranges of changes in the interchangeability criteria that allow a particular combustible gas to enter the gas transportation and gas distribution system.

The expansion of such ranges opens up the possibility for a larger number of combustible gases with various characteristics to acquire the status of permitted for use and obtain the right to enter the gas supply system. And suppliers of combustible gases are interested in this.

But it is necessary to remember that an important task today is to achieve high indicators of safety of use, energy efficiency and environmental safety at the stage of heat generation using combustible gases. And the expansion of the range of gas interchangeability indices does not contribute to solving this problem.

And vice versa, narrowing the regulatory range of interchangeability criteria reduces the list of combustible gases that can enter the country's gas transportation system, reduces the diversification of combustible gases. But at the same time, the issue of the possibility of ensuring high stability, efficiency and environmental safety of gas combustion equipment is resolved. At the same time, the possibility of burning those gases that do not fall within the permissible interval still remains – they can be burned in the form of mixtures with other gases to achieve normalized interchangeability indicators.

This approach to solving the ultimate task of ensuring the efficient use of energy sources is more balanced and correct.

It is important to realize that for each group of gases, according to the requirements of modern standards [15], the industry must produce its own type of gas-burning and gas-burning equipment,

Table 1. Classification of flammable gases according to the Wobbe index

Groups of gases of the second family	Prime Wobbe number at $t = 15$ °C, $p = 1013.25$ mbar, MJ/m ³	
	minimum	maximum
Group H	45.7	54.7
Group L	39.1	44.8
Group E	40.9	54.7

which must correspond to a specific group of gases. This is explained by the fact that gas equipment and burners manufactured for group H cannot be used to burn gases of another group without changes in the design of the burners, or changes in the operating settings of the burners and equipment.

For each group, the standards define, respectively, the test gases used in the production of gas equipment:

- reference – with the best performance indicators of the equipment (for gases E and H, gas G20 is taken as the reference gas; and for gas group L – gas G25). The interchangeability indicators of other gases-substitutes are compared with the reference gases;

- limit – with the largest permissible deviations from the best performance indicators of the equipment.

To determine the permissible deviations of the Wobbe index from the average values according to the current and effective standards in Ukraine [15], the data in Table 1 was converted from absolute values to relative values (in %) from the average values for each group of index values for the most common groups of gases. The results of the calculations are given in Table 2.

Therefore, according to the requirements of [15], the deviation of the Wobbe index for combustible gases of different groups in the range from 7 % to 14 % means their non-interchangeability in terms of thermal power according to the Wobbe index.

In addition, another index of interchangeability of gases in terms of thermal power is the Know index, included in the standards [15].

The Know index ($J(K)$) is one of the early in-

Table 2. Permissible values of deviations of the Wobbe index according to the requirements of DSTU, GOST, EN 437:2018, % of the average values

Groups of gases of the second family	Average value of the Wobbe index	Permissible deviation of the index from the average value according to [15], %	
		in the lower direction	in the higher direction
Group H	50.2	9	9
Group L	41.95	7	7
Group E	47.8	14	14

stances of interchangeability in terms of thermal power and a variation of the Wobbe index:

$$j_{(K)} = \frac{H_i - 0.65 \cdot 10^7}{\sqrt{d}}. \quad (2)$$

For proper interchangeability, it is necessary that the Know index for the main gas and the substitute gas differ by no more than 5 % [16]. A value of more than 5 % indicates that the equipment is not working properly.

The authors performed the definition and analysis of the combustible characteristics and the Wobbe index, as one of the interchangeability criteria, for a wide class of natural and alternative types of combustible gases produced and used in Ukraine. The purpose of such calculations was to determine the physicochemical properties of gases and the possibility of interchangeability in comparison with the reference gas of each of the classification groups.

The study of the physicochemical properties of combustible gases was carried out on experimental stands. For example, the determination of the flame propagation speed was carried out by the Michelson method using a Bunsen burner [17].

The experimental setup for determining the flame propagation velocity (Fig. 1) consists of a gas injection burner 1 equipped with a nozzle for

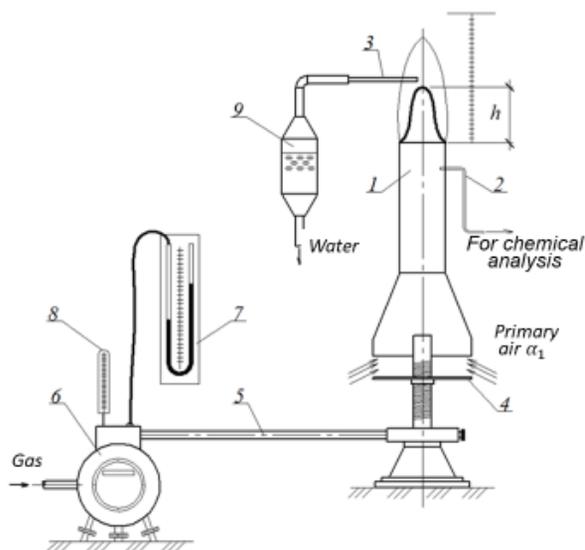


Figure 1. Schematic of the experimental setup for determining the flame propagation velocity by the Michelson method [17].

sampling the gas-air mixture 2, combustion products 3, an adjusting washer 4 for changing the composition of the mixture, a gas pipeline 5 that transports gas from the gas meter 6 to the burner 1. The gas meter is equipped with a water U-shaped manometer 7 and a thermometer 8 that measure the pressure and temperature of the gas in the meter 6, a container for sampling 9 and a stopwatch. The analysis of the gas mixture and combustion products for the presence of oxygen in it was performed using a Testo gas analyzer.

The results of the study are given in Table 3.

The upper limit of combustion for pure hydrogen is significantly higher compared to the above gases and is 75 % vol., and the lower limit is 4 % vol. The flame propagation speed significantly exceeds the data indicated in the Table 2 and is 2.67 m/s, and the highest simple Wobbe index is 48.47 MJ/m³. Analysis of the data in the table and the combustible characteristics of hydrogen as a gas that can replace hydrocarbon energy carriers shows that a change in the composition of the gas is accompanied by significant changes in its physical and chemical properties and combustible characteristics. So significant that the simple Wobbe index, which is taken as the main index of interchangeability, differs by type of combustible gases.

Significant differences in the value of the Wobbe index are even for some natural gases from different deposits. All this indicates their non-interchangeability, that is, the impossibility of effective use of gas equipment if the properties of the combustible gas change.

The analysis showed that most of the natural gases from various fields in Ukraine belong to group H. Hydrogen itself, as a gas that should turn Europe into the first climate-neutral continent, where greenhouse gas emissions into the atmosphere will not exceed the volume absorbed by the ecosystem, belongs to group E. It seems that this group was created for gases containing hydrogen.

A significant amount of gas equipment continues to be supplied under group L or E. This is a consequence of the recent preferential receipt of natural gas from purely gas fields from the aggressor country in the war in Ukraine. Manufacturers should now focus on producing equipment intended for the exploitation of the most widespread group of combustible natural gases in the country from their own fields. And the classification of these gases should comply not with outdated but with current regulatory requirements implemented

in Ukraine [15].

Regarding the use of hydrogen in a mixture with natural gas, which is relevant today, the requirement to achieve permissible changes in the Wobbe index for the natural gas being replaced and the substitute gas (a mixture of natural gas and hydrogen) is no longer met for a mixture with a hydrogen content of 20–25 %. This is confirmed by studies [18]. Thus, it is impossible to ensure the transition of the burner operation from natural gas to a combustible mixture with a hydrogen content of more than 20–25 % without making changes to the design of the burners and their operating modes, as well as the design and operating modes of the draft-blow devices of the installation. Such gases are not interchangeable. Analysis of other criteria and indices of interchangeability [19, 20] – the Know, Dutton, Weaver indices, AGA and Delburg methods – also indicates the fact of the lack of interchangeability of natural gas and its mixture with hydrogen under the condition of an even lower hydrogen content – about 15–20 % by volume.

But the creation and combustion of combustible gases with a lower hydrogen content (10–13 %) is possible, giving a broad perspective on the use of hydrogen as the main gas, which ensures the solution of decarbonization problems.

Studies conducted by the authors on the combustion of refinery gas with a variable hydrogen content from 20 to 54 % vol. confirm that the combustion of gases with a significant amount of hydrogen (more than 20 %) leads to cardinal changes in the operation of gas burner devices and the mass transition of their operation to the flame jump mode. The emission heat transfer of torches and convective heat exchange on heating surfaces also change. Other authors note changes that occur in the processes of nitrogen oxide formation when changing the combustion process of fuels of different composition [20–22].

One of the possible ways of burning different gases in the same gas burner devices without significant changes in their design is to change the gas pressure in front of the burner. To implement the transition from one combustible gas to another, it is also necessary to change the set operating parameters of its operation. After that, it is necessary to check the value of the modernized interchangeability criterion – the extended Wobbe index.

The extended Wobbe index includes the gas pressure in front of the burner and is determined

Table 3. The results of the study of combustible gases

Name of gas, characteristics Natural gases from various fields			Reference gases		Producer gas	Biogas	Biomethane
Gas 1	Gas 2	Gas 3	G25	G20			
Gas composition, % vol.							
CH ₄ - 93.26	CH ₄ - 91.26	CH ₄ - 86.3	CH ₄ - 86	CH ₄ -100	CH ₄ - 2	CH ₄ - 57.5	CH ₄ - 98
C ₂ H ₆ - 3.36	C ₂ H ₆ -3.02	C ₂ H ₆ - 0.2	N ₂ - 14		H ₂ - 17.5	H ₂ - 1.5	N ₂ - 0.5
C ₃ H ₈ - 0.77	C ₃ H ₈ - 0.87	C ₃ H ₈ - 0.15			CO - 22.5	N ₂ - 3	CO ₂ - 1.5
C ₄ H ₁₀ -0.43	C ₄ H ₁₀ -0.32	C ₄ H ₁₀ -0.05			N ₂ - 43.5	CO ₂ - 38	
C ₅ H ₁₂ -0.42	C ₅ H ₁₂ -0.36	N ₂ - 13.13			CO ₂ - 14.5		
N ₂ - 1.58	N ₂ - 0.53	CO ₂ - 0.17					
CO ₂ - 0.18	CO ₂ - 3.61						
The content of C ^p in the gas composition, %							
73.6	74.9	59	58.3	74.8	15	58	74
The content of H ^p in the gas composition, %							
23.8	23.9	19	19.6	25.1	2	23	24
The ratio of C ^p /H ^p in the elemental composition of the gas							
3.09	3.13	3.1	2.97	2.9	7.5	2.5	3.1
Upper limit of combustion, %							
14.75	14.65	14.97	17.0	15.0	79.95	28.46	15.3
Lower combustion limit, %							
4.75	4.69	4.9	5.7	5.0	13.98	8.14	5.1
Laminar flame propagation velocity S _L (at $p = 0.1$ MPa, $t \approx 25$ °C), m/s							
0.37	0.354	0.37	0.37	0.48	0.48	0.13	0.37
Combustion air consumption (at $t = 0$ °C, $p = 1013.25$ mbar), m ³ /nm ³							
9.93	9.84	9.34	8.19	9.5	1.14	5.51	9.34
Wobbe index ($t = 15$ °C, $p = 1013.25$ mbar), MJ/m ³							
50,79	48,35	42,01	41,49	50,69	5,92	22,70	48,95
Extended Wobbe index ($t = 15$ °C, $p = 1013.25$ mbar), MJ/m ³							
54,52	51,9	45,01	44,44	54,3	6,53	24,3	52,43
Required gas pressure before the burne, kPa							
0.89	0.955	1,266	1.27	-	63,57	4,34	1,05
Flame separation speed, m/s							
3.02	2.95	1.88	2.96	1.88	2.52	1.88	2.24
Flame jump speed, m/s							
0.26	0.24	0.38	0.23	0.38	0.46	0.08	0.17

according to the dependence (3) [23]:

$$W_i^p = H_i \cdot \sqrt{P_i/d_i}, \quad (3)$$

where P_i is the gas pressure before the burner, kPa.

The gas pressure that must be maintained to ensure a constant thermal power of the unit when replacing one combustible gas with characteristics P_1, ρ_1, H_1 with another – with characteristics P_2, ρ_2, H_2 , is proposed to be calculated according to dependence (3):

$$P_2 = P_1 \frac{\rho_2}{\rho_1} \left(\frac{H_1}{H_2} \right)^2. \quad (4)$$

For municipal and household devices, the nominal passport pressure of natural gas in front of the burners is 1270 Pa [24]. According to clause 2.5 of the DBN Gas Supply [24]: “The gas pressure in front of household gas appliances should be taken in accordance with the passport data of the devices...” Maintaining a constant thermal power and a constant Wobbe index when switching to burning a gas mixture with a hydrogen content of, for example, 30 % vol. requires, according to the given dependence, an increase in the pressure in front of household gas appliances to 1500 Pa. This will require changes in the operation of gas distribution networks and gas control points that supply gas to consumers.

For forced-air burners, a change in pressure is accompanied by a change in the diameter of the fire holes. This can be done using the adjusting disk on the fire nozzle (“combustion head”) of the burner, depending on the heat of combustion and the density of the combustible gas.

For injection burners, it is important not only to ensure a constant burner power when switching

from one gas to another, but also to withstand the conditions under which the required amount of primary air will be injected into the burner. The authors have highlighted the dependencies for determining the necessary changes in the operation of such burner devices in [25]. Making such changes to the operation of the equipment will provide the necessary values and other criteria for interchangeability – breakthrough, separation and yellow tongues of flame.

The analysis of the interchangeability of gases in relation to the above-mentioned parameters of the burner devices was performed for various combustible gases by determining the following criteria:

- AGA index of incomplete combustion of fuel – C(A);
- Weaver criterion of incomplete combustion of fuel – A(W);
- AGA index of soot formation – IY(A);
- Weaver criterion of soot formation – JY(W);
- AGA index of flame separation – IL(A);
- Weaver criterion of flame separation – JL(W);
- AGA index of flame jump – IF(A);
- Weaver criterion of flame jump – JF(W).

When determining such criteria, natural combustible gases from Ukrainian deposits and alternative types of gases were taken as substitute gases. Test limit gases of group N were taken as limit gases. The composition of such gases is given in Table 4.

The results of the interchangeability criteria calculations are given in Table 5.

The limit values of the criteria are specified in the section “name of gas” of Table 4. For example, the incomplete combustion index of AGA when comparing the substitute gas with the limit gas of the device must be within $0.85 \leq C(A) \leq 1.15$. If the value of the index $C(A) > 1.15$, then there is

Table 4. Type, composition and characteristics of test gases [12, 26]

Combustible gas group	The test characteristics of the gas combustion equipment operation		
	Flame jump	Flame break	Completeness of fuel combustion and soot formation (yellow flashes of flame)
Second category, group H	G22 CH ₄ – 77 % vol. H ₂ – 23 % vol. W _i = 47.87 MJ/m ³ H _i = 31.86 MJ/m ³	G23 CH ₄ – 92.5 % vol. N ₂ – 7.5 % vol. W _i = 45.66 MJ/m ³ H _i = 34.96 MJ/m ³	G21 CH ₄ – 87 % vol. C ₃ H ₈ – 13 % vol. W _i = 45.28 MJ/m ³ H _i = 54.76 MJ/m ³

Table 5. Determination of interchangeability criteria for chemical under-combustion. flame spread and flame separation

Name of gas, characteristics	Natural gases from different deposits			Reference gases		Producer gas	Biogas	Bio-methane
	Gas 1	Gas 2	Gas 3	G25	G20			
Gas composition, % vol.	CH ₄ – 93.26	CH ₄ – 91.29	CH ₄ – 86.3	CH ₄ – 86	CH ₄ – 100	CH ₄ – 2	CH ₄ – 57.5	CH ₄ – 98
	C ₂ H ₆ – 3.36	C ₂ H ₆ – 3.02	C ₂ H ₆ – 0.2	N ₂ – 14		H ₂ – 17.5	H ₂ – 1.5	N ₂ – 0.5
	C ₃ H ₈ – 0.77	C ₃ H ₈ – 0.87	C ₃ H ₈ – 0.15			CO – 22.5	N ₂ – 3	CO ₂ – 1.5
	C ₄ H ₁₀ – 0.43	C ₄ H ₁₀ – 0.32	C ₄ H ₁₀ – 0.05			N ₂ – 43.5	CO ₂ – 38	
	C ₃ H ₁₂ – 0.42	C ₃ H ₁₂ – 0.36	N ₂ – 13.13			CO ₂ – 14.5		
	N ₂ – 1.58	N ₂ – 0.53	CO ₂ – 0.17					
	CO ₂ – 0.18	CO ₂ – 3.61						
C(A) ≤ 1.15	0.88	0.81	0.63	1.00	1.00	0.11	0.25	0.83
JI(W) ≤ 0	-0.10	-0.13	-0.27	0.00	0.00	-0.64	-0.47	-0.14
IY(A) ≥ 1	1.27	1.36	1.74	1.00	1.00	1.21	4.48	1.38
JY(W) ≤ 0	-0.24	-0.30	-0.47	0.00	0.00	-1.18	-0.83	-0.35
IL(A) ≤ 1	0.91	0.96	1.09	1.00	1.00	8.22	1.94	0.93
JL(W) ≥ 1	1.15	0.97	0.89	1.00	1.00	0.05	0.39	1.11
IF(A) ≤ 1	0.759	0.776	0.857	0.93	1.000	7.39	1.27	0.789
JF(W) ≤ 0	-0.47	-0.40	-0.25	1.00	0.00	0.72	0.21	-0.42

a tendency for chemical underburning. The Weaver incomplete combustion index when comparing the substitute gas with the limit gas of the device must be $JI(W) \leq 0$. If the value of the Weaver index becomes $JI(W) > 0$, then there is a tendency for chemical underburning. Provided that the soot formation index of AGA becomes $IY(A) < 1$, then there is a tendency for soot formation during the combustion process. And according to the Weaver criterion, the danger of soot formation occurs if the index $JY(W) > 0$.

The danger of separation occurs if the AGA index $IL(A)$ acquires values greater than 1.0, and the Weaver criterion $JL(W)$ acquires values less than one compared to the limiting gas.

The danger of flame jump occurs if the AGA index $IF(A)$ acquires values greater than 1.0, and the Weaver criterion $JF(W)$ becomes greater than 0.

Analysis of the obtained data shows that in relation to the formation of chemical unburned products, flashback and flame separation, a significant number of gases are not interchangeable. This leads to complications in ensuring the processes of stable and efficient combustion of such combustible gases.

Thus, the interchangeability criteria allow for a universal assessment of the interchangeability of combustible gases by the criterion of thermal

power, torch stability and the formation of chemical unburned products. In addition, the extended Wobbe index makes it possible to obtain dependencies for recalculating the operating and design parameters of burners for the possibility of their use for non-interchangeable gases. This significantly expands the capabilities of gas equipment manufactured for the use of combustible gases of a certain group.

Analysis of the properties of various combustible gases presented in Table 1 and Table 2, as well as experimental studies that were performed on oil refinery gases of variable composition of an oil refinery showed that a change in the gas composition is accompanied by a change in the C^p/H^p ratio in the elemental composition of gases. And a change in the ratio of carbon and hydrogen in the gas composition leads not only to changes in the combustible properties of the gas, but also changes the heat transfer in the combustion devices of gas-burning equipment.

If the composition of the combustible gas and its properties do not correspond to the group of gases for which the gas equipment is manufactured and the gases differ significantly in combustible characteristics, the preparation and combustion of mixtures of different combustible gases is proposed. In this case, the operation of devices for prepa-

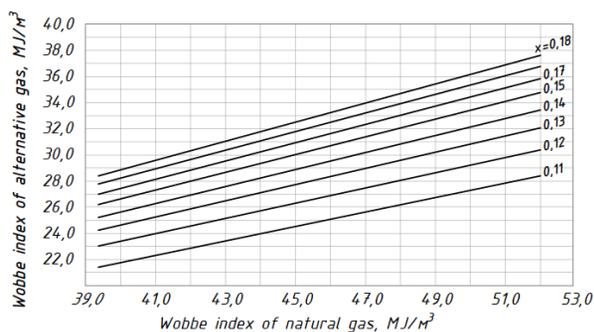


Figure 2. Nomogram for determining the composition of a gas mixture to achieve the required criterion for the interchangeability of a gas mixture. (x is the proportion of alternative gas (part. units) by volume that must be mixed into the mixture with natural gas to obtain the required value of the Wobbe index).

ring gas mixtures should be based on the preparation of such a gas composition that will meet the required interchangeability criterion. In the case of using alternative types of gases, biogas, or generator gas, the main component of such a mixture should be natural gas.

In Fig. 2. a nomogram is presented for determining the composition of such a gas mixture, depending on the values of the Wobbe criterion for each type of gas.

Conclusions

An analysis of the physical and chemical characteristics of natural and alternative types of combustible gases was performed. Experimental studies of the combustion of refinery gases with a variable composition of combustible gas in the furnaces of an oil refinery were conducted. The results of the work indicate that neglecting the change in the physical and chemical characteristics and composition of combustible gases supplied to consumers, the use of gas equipment manufactured for one group of gases for the combustion of other non-interchangeable gases leads to negative consequences. This is a change in the thermal power of the units, a change in the operating conditions of the gas-air tract and thrusters, the size of the torch and the conditions of heat transfer in the furnace space. An uncontrolled change in the composition of the fuel leads to a decrease in the completeness of fuel combustion, a change in the coefficient of excess air in the combustion products and a deterioration in the efficiency of fuel combustion units.

Burning non-interchangeable combustible gases without proper changes in the burner design and adjustment of the unit's operating parameters can lead to a reduction in the adjustment range and disruption of the stability of the burner flame; a decrease in the efficiency of gas use. A comprehensive indicator of gas interchangeability is the Wobbe criterion, which is the basis for the classification of combustible gases by groups.

The stability of the physical and chemical parameters of the gas and the value of the Wobbe criterion must be constantly monitored according to fuel quality certificates. Particular attention must be paid to the deviation of the Wobbe criterion for various combustible gases from the nominal value established by the contractual conditions of gas supply. This index should not change by more than 5 % of the nominal value. The obtained dependencies make it possible to use gas-burning equipment for non-interchangeable gases subject to changes in the operating parameters of the equipment and its design characteristics. It is recommended to urgently transition from the current outdated to the current regulatory documents that regulate the current level of requirements for the quality of combustible gases and the efficiency of their use. Reference to the "Code of Gas Transportation Systems" adopted in 2015 by the NERC Resolution must be considered unacceptable in the presence of current regulatory documents (state standards) that implemented European requirements for combustible gases. As an argument, it is enough to mention only that the document currently used in the field of using gas as a fuel does not contain a single quantitative indicator at all that would characterize the possibility of interchangeability and energy efficiency of using combustible gases. What is the point in such a case of a permit to supply an alternative type of combustible gas to the country's gas transportation system if, according to its physical and chemical characteristics, this gas meets the requirements of regulatory legal acts for natural gas. And the problem then lies in which regulatory legal acts should be taken into account.

It has been found that a change in the ratio between the carbon and hydrogen content in the elemental composition of combustible gases of different origins leads to a change in heat transfer on the heating surfaces of heat-generating equipment, which needs to be taken into account when designing it.

Analysis of the physicochemical properties of combustible gases available for use makes it possible to develop recommendations for the production and distribution of gas equipment for such a group of combustible gases that is typical for supply in the gas distribution system of each country or region.

The performed analysis and research allow us to state that the use of a mixture of natural gases with 10–12 % hydrogen is permissible for injection burners of household gas stoves and other equipment for municipal and household purposes. It is important that changes in the design of gas equipment and its operating mode are not required. For industrial gas blow burners, it is possible to recommend the possibility of safe operation of devices on a mixture with a hydrogen content of up to 20–22 % vol. This is explained by the presence of flame stabilizers in such burners.

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Дослідження ефективності спалювання водню, альтернативних та природних невлазозамінних газів

Анотація. Наведено результати визначення критерію взаємозамінності газів. Виконано аналіз можливості адаптації існуючих газоспалювальних установок для ефективного та стабільного використання широкого спектра горючих газів. Показано, що навіть природні гази з різних родовищ не завжди є взаємозамінними. Розроблено рекомендації, які дають можливість використовувати навіть невлазозамінні гази на одному й тому ж газоспалювальному обладнанні за рахунок зміни режимних налаштувань або незначної зміни конст-руктивних характеристик обладнання. Наведено результати дослідження теплообміну в камері згоряння при зміні складу горючих газів та пов'язаних з цим змін випромінювальної здатності продуктів згоряння. Дано рекомендації щодо організації процесу спалювання невлазозамінних газів, у тому числі за рахунок створення сумішей горючих газів із забезпеченням необхідних критеріїв взаємозамінності. Метою роботи є дослідження можливості ефективного спалювання альтернативних видів штучних та синтетичних горючих газів, у тому числі водню, а також невлазозамінних природних газів в існуючому газоспалювальному обладнанні. Досліджено властивості горючих газів, характерних для газорозподіль-

них систем України, та їх відповідність критеріям взаємозамінності та газоспалювальному обладнанню, що виробляється та постачається для промислових та комунальних потреб. Актуальність питань забезпечення взаємозамінності газів підтверджується впровадженням у національне законодавство України нормативно-правових актів щодо показників якості горючих газів та ефективності їх використання. Результати дослідження забезпечують можливість безбар'єрного поступового впровадження альтернативних видів газів та поступового переходу до спалювання газів із вмістом водню без кардинальних змін конструкції існуючих пальників та режимів їх роботи. *Бібл. 26, рис. 2, табл. 5.*

Ключові слова: горючі природні та альтернативні гази, критерії взаємозамінності, фізико-хімічні та горючі властивості газів, ефективність та стабільність використання горючих газів.

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Дослідження потреб енергосистем у накопичувачах електроенергії при масовому впровадженні електростанцій негарантованої потужності

Анотація. Акумуляторні системи зберігання енергії завдяки доступності, високій швидкості, значній енергетичній щільності та достатній потужності набули широкого застосування. Однак їх вартість залишається доволі високою. У статті розглянуто питання розроблення методичного підходу щодо визначення доцільних потреб в ємності та потужності накопичувачів електроенергії для енергосистем при наявності в їх структурі значної кількості вітрових електростанцій для забезпечення режиму роботи цих електростанцій з прогнозованою потужністю, що і є метою дослідження. Для досягнення поставленої мети проаналізовано добові графіки електричних потужностей вітрових електростанцій Об'єднаної енергосистеми України за період 2017–2019 рр., визначено їх коефіцієнти використання встановленої потужності, обґрунтовано вибір інтервалу прогнозування потужності, створено розрахункову модель для виконання статистичного аналізу. За допомогою розрахункової моделі побудовано графіки розподілу ймовірності потреб в акумуляції та графіки приведених потреб в акумуляції у залежності від ймовірності їх покриття. Аналіз показав високе спів-