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INTERCHANGEABILITY AND STANDARDIZATION OF THE PARAMETERS OF COMBUSTIBLE GASES WHEN USING HYDROGEN

Alexander Shkarovskiy[1,2]*, Anatolii Koliienko[3], Vitalii Turchenko[3]

[1]Saint Petersburg State University of Architecture and Civil Engineering
2-nd Krasnoarmeiskaya St. 4, St. Petersburg, Russia
[2]Koszalin University of Technology
Sniadeckich St. 2, 75-453 Koszalin, Poland
[3]National University “Yuri Kondratyuk Poltava Polytechnic”
Piershotravnevyj Ave. 24, Poltava, 36011 Ukraine

*Corresponding author: szkarowski@mail.ru

Abstract

Introduction and purpose of the study: The paper presents results of studies aimed to provide a rationale for the possibility of a gradual transition to hydrogen combustion in gas supply to domestic and commercial consumers without changes in the design and operation of burners. For this purpose, we have considered tasks of determining the indicators of interchangeability for natural gas and its mixtures with hydrogen. The main characteristics of combustible gases with various hydrogen content in a mixture have been studied. We have established the impact of the hydrogen content on the heat rate, emissions of harmful substances, as well as light back and flame lift phenomena. We have also analyzed the available interchangeability criteria and their applicability when using natural gas/hydrogen mixtures. The impact of the hydrogen content on the radiation heat transfer in the furnaces of gas equipment is described in the paper for the first time. **Methods**: The methodology of the paper is based on a critical analysis of available literature data on combustible gases interchangeability as well as theoretical and experimental studies performed by the authors. We have derived dependencies that allow us to determine the possibility of gas equipment transition to the combustion of natural gas/hydrogen mixtures. We have also developed recommendations on the permissible hydrogen content in a natural gas/hydrogen mixture that would ensure the efficient, safe, and green use of such fuel in domestic and commercial heating units. **Results**: Scientific findings and practical results of the study make it possible to implement partial gradual cost-effective decarbonization in the area of gas fuel utilization as an intermediate stage of transition to more extended hydrogen combustion.

Keywords

Gas supply, decarbonization, natural gas, hydrogen, mixtures, interchangeability, permissible content.

Introduction

Currently, studies and pilot projects related to the use of hydrogen as a fuel are of the most immediate interest. The reason for such interest is the possibility of decarbonization of the atmosphere through reaching zero CO_2 emissions with combustion products and reducing the impact on global climate changes (European Commission, 2020).

However, as often happens, the road from the idea to its technical implementation is long and difficult. First of all, it is worth mentioning numerous technical and economic issues of hydrogen production, storage, transportation, and use, which are nowadays contradictory. This is especially when we refer to great and almost global plans for transition to this type of fuel (Grib, 2019). The so-called catalytic steam reforming of hydrocarbons is a quite simple and well-mastered method. However, the process is accompanied by such quantities of CO_2 emissions that the thesis on the green nature of hydrogen fuel does not make sense. Well-known hydrous pyrolysis does not have this drawback, but it is 1.8–3 times more expensive than reforming. Electric power required for electrolysis can be of green origin only so as not to bump into the issue of CO_2 plume (Konoplyanik, 2020). In our opinion, the necessary investment and functional-cost analysis of many related issues is still far from completion.

Despite this, the idea has already won recognition. In 2019, the EU presented a hydrogen strategy as part of the European Green Deal (European Commission, 2019). It is planned that hydrogen will be able to replace carbon energy sources, and by 2050 it will transform Europe into the first climate-neutral continent where greenhouse gas emissions into the atmosphere will not exceed the volume consumed by the ecosystem. The EU states are willing to invest 180 to 470 bn EUR into this project by 2050. Within the framework of this strategy, there is a project to provide the EU with hydrogen with a hydrogen production capacity of 80 GW.

Decisions concerning hydrogen economy development, including in the Russian Federation, are made at the governmental level (Government of the Russian Federation, 2020). The largest energy providers negotiate the use of entire territories for the construction of hydrogen production enterprises (RBC, 2021c). This trend is also observed in cooperation at the international level (RBC, 2021a).

However, the issues of hydrogen use are not limited to the matters of its production, storage, and transportation. The thing is that hydrogen and hydrocarbon fuels, such as natural gas, are combustible gases disparate in terms of their main indicators. Calorific value and density, air consumption and volume of combustion products, flame speed and flammability limits — all these most important characteristics differ several times (Staskevich et al., 1990). Therefore, full replacement of gas burners rather than their adjustment is required. New devices can be developed for dozens and hundreds of units, as is the case with power turbines (RBC, 2021b). However, for hundreds of thousands and even millions of low-power devices, such replacement in one go is impossible. In this situation, the idea to use hydrogen in mixtures with natural gas seems most reasonable (European Commission, 2020). It is not a case of zero CO_2 emissions, but each 10% of hydrogen in such a mixture make it possible to proportionately reduce carbon dioxide emissions into the atmosphere (Szkarowski, 2020).

Analysis of the current state of the issue

When studying if it is possible to use such mixtures in practice, the issue of permissible hydrogen content is the key factor. The solution to this problem is a typical trade-off. On the one hand, there is a wish to increase the share of hydrogen and its environmental effect. On the other hand, it is required to ensure compliance with the fuel utilization efficiency and safety principles and minimize the volume of investments necessary for the transition of gas burner and furnace units from pure natural gas they were designed for to natural gas/hydrogen mixtures (Flórez-Orrego, 2011).

The matters of interchangeability of combustible gases are not new for the theory and practice of fuel consumption (Knoy, 1941, 1953). In many countries, the issue of transition from synthetic gases to natural gas was handled at different times (Gilbert and Prigg, 1956). Nowadays, it can be biogas, generator gas, refinery gas, propane-butane gas, liquefied natural gas (LNG), or their mixtures with each other and air (Jones, 2005).

Hydrogen or its mixtures with other gases may be a similar alternative. For example, refinery gas with high hydrogen content in a mixture with natural gas is used at refineries as a fuel for oil refinery furnaces and oil refinery units (Kolienko and Kolienko, 2011).

For the majority of EU countries that receive natural gas via gas trunk lines from the Russian Federation, it is the main type of fuel. However, it does not rule out the possibility of using other types of gas fuel. Therefore, the standardization of interchangeability of various gases in such countries is reflected at the appropriate level (Delbourg and Lafon, 1971).

Subject, tasks, and methods

Interchangeability can be defined as the ability of combustible gas to be substituted by another without the need to adjust gas burner units (GBUs) or other equipment of gas devices, change the operation mode or settings of such equipment. The units will continue to operate safely and satisfactorily (International Organization for Standardization, 2013; Honus et al., 2016)

Therefore, the possibility of a seamless transition from one type of gas fuel to another while preserving (or with permissible changes to) equipment characteristics exists only for interchangeable gases. These characteristics are as follows:

– heat rate ***N***, kW;

– energy conversion efficiency η, %;

– steady operation of GBUs without light back or flame lift;

– complete combustion (permissible concentration of incomplete chemical combustion products in combustion products), mg/m^3 or vol.%;

– absence of yellow tipping indicating pyrolytic processes and sooting related to the insufficient air intake for combustion (total or primary air).

Therefore, the subject of the study is the effective and safe utilization of various gases in commercial and domestic sectors in terms of the increasingly widespread use of hydrogen and its mixtures.

It is known from the practice of combustible gas combustion that steady and efficient gas combustion in the flow significantly depends on the operating parameters of this process. Such parameters include the following: air and gas consumption, including primary air (for burners with two-stage air supply); ratio between actual and theoretical air consumption (air excess factor α); gas and air velocity, etc. (Halchuk-Harrington and Wilson, 2006).

The stable position of the flame front in space and absence of light back and flame lift are ensured by the equality of the flame speed and the gas-air mixture speed at each point of the front. In turn, this equality depends on the properties of the fuel, efficiency of mixing processes, flame holding methods, and burner heat output. That is why the composition as well as physical and chemical properties of the gas are crucial for the interchangeability of combustible gases and fuel utilization efficiency.

The region of efficient and steady combustion is limited to the regions of loss of flame stability (light back and flame lift) and incomplete combustion with preceding yellow tipping indicating sooting. The diagram in Fig. 1 (Halchuk-Harrington and Wilson, 2006) shows these regions in the "burner heat output" – "primary air excess factor" coordinates.

The diagram is somewhat conditional since it uses only concepts, without any numerical values. From this perspective, the diagram given in Fig. 2 (Staskevich et al., 1990) is more conclusive. It presents a steady and efficient combustion region in the "gas/air mixture velocity" – "primary air excess factor α_1" coordinates. Please note that the gas/air mixture velocity is associated with the gas flow rate and burner heat rate.

Therefore, when resolving the issue of gas interchangeability, it is required to ensure steady and efficient operation not only without changes to the GBU design while complying with the rated capacity but also within the whole range of the output control.

According to the effective standards (Euro-Asian Council for Standardization, Metrology and Certification, 2012; European Committee for Standardization, 2021), all types of combustible gases are classified first by gas family and then by group and subgroup. For example, natural gases are in Family 2 where high-methane gases are in Group E. Gases of the same group have the same combustion characteristics and are clustered by the value of one of the interchangeability indicators — the (superior) Wobbe index W_s, MJ/m^3:

$$W_s = \frac{H_s}{\sqrt{\bar{\rho}}} = \frac{H_s}{\sqrt{\frac{\rho_g}{\rho_a}}}, \quad (1)$$

where H_s — the superior calorific value, MJ/m^3; $\bar{\rho}$ — the relative gas density; ρ_g, ρ_a — the gas density and air density, respectively, all other factors being equal, kg/m^3.

For the matter at hand, the following is important: the fact that the Wobbe index of other gases differs by not more than 5% means that the design and operating parameters of GBUs used for burning gases of this group do not require any changes and the unit heat rate will be preserved.

Natural gas of groups L and E is mainly supplied to Europe from Russia via gas trunk lines. According to the above requirements, the superior Wobbe index for group L gases shall be 39.1–44.8 MJ/m^3 (the volume is given for a temperature of 15°C and a pressure of 1013.25 mbar). Based on Eq. (1), the calorific value of such gas shall be 29.3–34.5 MJ/m^3. For group E, these limits are as follows: W_s = 40.9–54.7 MJ/m^3; H_s = 31.3–44.4 MJ/m^3.

However, according to the same standard (European Committee for Standardization, 2021), to ensure safe and efficient GBU operation, the unit shall be tested by burning not the gas of this group but so-called test gases, each of which, in terms of composition, is critical for certain equipment performance characteristics. Table 1 provides characteristics of test gases for group L and E gases.

Therefore, the Wobbe index is no longer the only interchangeability criterion. The equality of the Wobbe index for different gases is a necessary but not sufficient condition of their full interchangeability. **The purpose of this study** was to determine principles for the reliable standardization of combustible gas interchangeability parameters.

As for the **methods**, we chose a comparative critical analysis of regulatory documents and available experimental data as well as performed theoretical and experimental studies in this field.

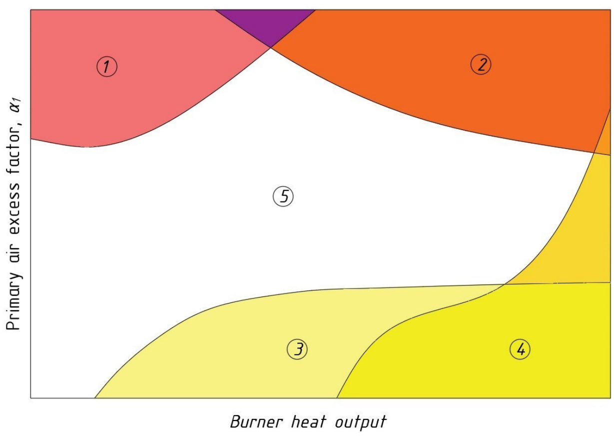

Fig. 1. Gas combustion diagram of the American Gas Association (AGA): 1 — the light back region, 2 — the flame lift region; 3 — the yellow tipping region, 4 — the incomplete combustion products region, 5 — the steady and efficient gas combustion region

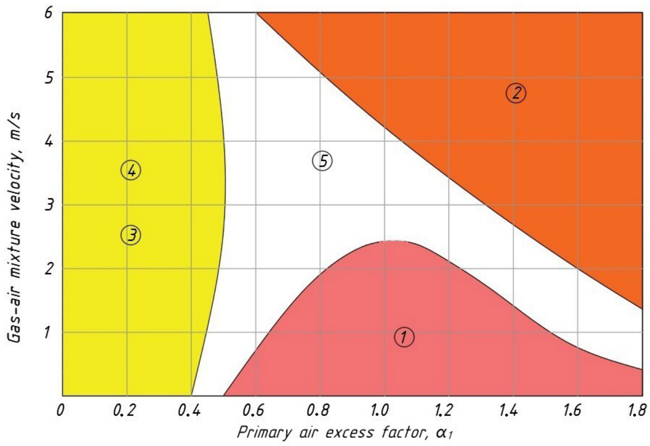

Fig. 2. Diagram of steady and efficient operation of an injection gas burner. The designations of the regions are the same as in Fig. 1

Table 1. Test gas characteristics

Combustible gas	Test No., test gas composition and characteristics for the following critical equipment operation modes:		
	Light back	Flame lift	Incomplete combustion and yellow tipping
Family 2, Group L	G25 CH_4 = 86 vol.% N_2 = 14 vol.% W_s = 41.52 MJ/m³ H_s = 32.49 MJ/m³	G27 CH_4 = 82 vol.% N_2 = 18 vol.% W_s = 39.06 MJ/m³ H_s = 30.98 MJ/m³	G26 CH_4 = 80 vol.% C_3H_8 = 7 vol.% N_2 = 13 vol.% W_s = 44.83 MJ/m³ H_s = 36.91 MJ/m³
Family 2, Group E	G222 CH_4 = 77 vol.% H_2 = 23 vol.% W_s = 47.87 MJ/m³ H_s = 31.86 MJ/m³	G231 CH_4 = 85 vol.% N_2 = 15 vol.% W_s = 40.90 MJ/m³ H_s = 32.11 MJ/m³	G21 CH_4 = 87 vol.% C_3H_8 = 13 vol.% W_s = 54.76 MJ/m³ H_s = 45.28 MJ/m³

Results and discussion

1. Preliminary analysis

As follows from Table 1, to check equipment for light back, test gas with a hydrogen content of **up to 23%** is used (G222 test gas). Such hydrogen content in a mixture with natural gas is already critical in terms of loss of flame stability. It is very important for the subsequent analysis.

It should be noted that State Standard GOST EN 437:2012 (Euro-Asian Council for Standardization, Metrology and Certification, 2012) did not become in Russia (as a natural gas exporter) the main document to determine gas quality and gas interchangeability criteria. When formulating gas quality requirements, the exporter uses State Standard GOST 5542-2014 (Interstate Council for Standardization, Metrology and Certification, 2015).

According to this document, the (superior) Wobbe index is the only indicator of gas interchangeability. Its value for natural gas shall be 41.2–54.5 MJ/m^3 (at a temperature of 20°C) and permissible deviation **from the nominal value** shall not exceed ±5%. This ensures the constant heat rate of the unit upon combustible gas substitution. There are no other gas interchangeability requirements in this document. Besides, the concept of the “nominal value” is not explained in any way. In practice, it is usually the value established in a gas supply agreement. However, the range of possible Wobbe index values according to the GOST (41.2–54.5 MJ/m^3) is no less than 32% relative to the lower limit for group E gases.

When the issue of interchangeability of natural gas and its mixture with hydrogen is analyzed more deeply, it should be noted that hydrogen and natural gas have drastically different characteristics. Table 2 compares the physical and chemical properties of methane (as the primary combustible component of natural gas) and hydrogen (Staskevich et al., 1990; Szkarowski, 2020).

Table 2. Some characteristics of methane and hydrogen (t = 20°C)

Combustion characteristic	Unit of measurement	CH_4	H_2
Superior calorific value H_s	MJ/m³	39.82	12.75
Superior Wobbe index W_s	MJ/m³	53.55	48.47
Inferior calorific value H_i	MJ/m³	35.88	10.79
Inferior Wobbe index W_i	MJ/m³	48.22	41.02
Flammability limits in a mixture with air: lower limit c_l upper limit c_u	vol.%	5.0 15.0	4.0 75
Stoichiometric air volume for complete combustion	m³/m³(gas)	9.52	2.38
Maximum combustion temperature	°C	2043	2235
Stoichiometric volume of combustion products	m³/m³(gas)	10.52	2.88
Maximum flame speed	m/s	0.37	2.67
Air excess factor at the flammability limits: at the lower limit at the upper limit	–	1.8 0.65	9.8 0.15
Gas density	kg/m³	0.71	0.089

Evidently, the differences in the combustion characteristics of methane and hydrogen are drastic. The stoichiometric air volume for complete combustion, the volume of combustion products, and the upper flammability limit that guarantees combustion without light back differ by 4 times, and the flame speed — by 7 times. It is extremely important to compare the Wobbe index for methane and hydrogen. It differs almost by 10%, which means that it is impossible to convert burners to hydrogen use without changing their design.

This confirms the relevance of the matter related to the use of not pure hydrogen but its mixture with natural gas, which has already been noted in the introduction. Here, the issue of permissible hydrogen content in such a mixture, ensuring a seamless transition to a new type of gas fuel, is pivotal. We calculated the main characteristics of the mixture with various hydrogen content. The calculation data are given in Table 3 and Figs. 3–5.

Table 3. Some characteristics of the natural gas/hydrogen mixture (***t*** = 20°C)

Characteristic	**Unit of measurement**	**H_2 content in the mixture, vol.%**		
		10	**30**	**50**
Density	kg/m³	0.65	0.53	0.40
Superior calorific value H_s	MJ/m³	37.10	28.36	23.33
Superior Wobbe index W_s	MJ/m³	52.18	49.58	47.08
Difference in the superior Wobbe index for the mixture and natural gas (W_s = 53.6 MJ/m³)	%	2.6	7.5	12.2
Inferior calorific value H_i	MJ/m³	33.38	28.36	23.33
Inferior Wobbe index W_i	MJ/m³	46.95	44.37	41.81
Difference in the inferior Wobbe index for the mixture and natural gas (W_i = 48.22 MJ/m³)	%	2.6	8.0	13.2
Flammability limits in the mixture with air: lower limit upper limit	vol.%	4.9 16.3	4.6 19.7	4.4 25.0
Air excess factor at the flammability limits: at the lower limit at the upper limit		2.2 0.58	2.70 0.55	3.62 0.5
Maximum mixture velocity at light back	m/s	0.19	0.26	0.37
Primary air excess factor at the boundary of yellow tipping	–	0.21	0.19	0.17
Stoichiometric air volume required for complete combustion	m³/m³(gas)	8.8	7.4	5.9
Volume of combustion products (α = 1.15)	m³/m³(gas)	11.1	9.3	7.6
Stoichiometric composition of combustion products: - water vapor H_2O - nitrogen N_2 - oxygen O_2 - carbon dioxide CO_2	vol.%	17.1 72.3 2.5 8.1	18.2 71.8 2.4 7.5	19.8 71.2 2.4 6.6

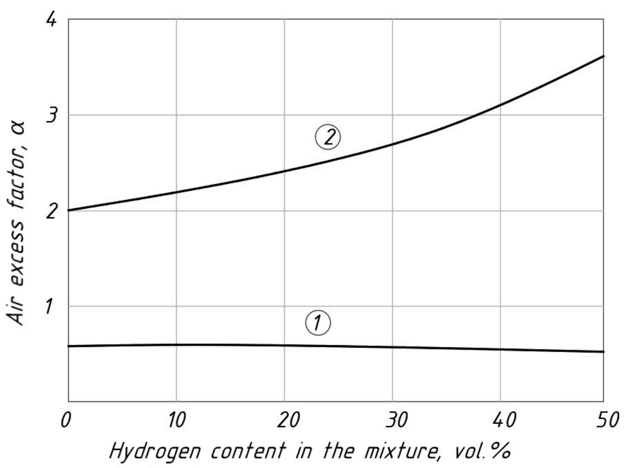

Fig. 3. Air excess factor at the lower (2) and upper (1) flammability limits

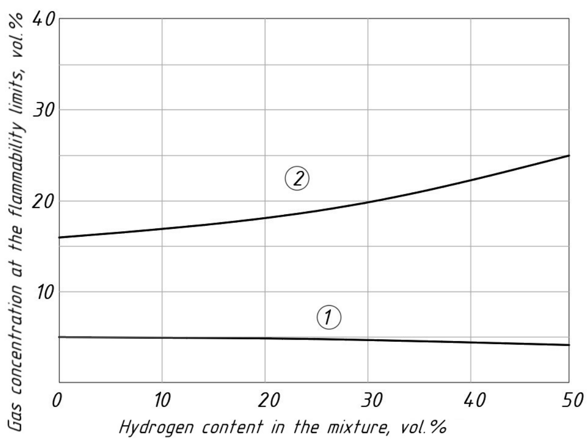

Fig. 4. Gas concentration at the lower (1) and upper (2) flammability limits

Comparison by the Wobbe index has a principal meaning for the analysis. It is not accidental that the comparison was also made by the inferior index value. The superior index value uses the concept of the superior calorific value that can be achieved only at the condensation of water vapors forming during combustion, which is achievable in a limited group of condensing equipment. Moreover, it is fundamentally impossible in household gas stoves.

The comparison shows that the permissible Wobbe index variation (5%) for the natural gas/hydrogen mixture is not met already at a hydrogen content of 20%. Therefore, it is impossible to ensure a transition from natural gas to a combustible mixture with a hydrogen content of more than 20% without changing the burner design and operating parameters when trying to preserve the burner heat rate. As for forced-draught gas burners, changes in the design and operating parameters of the draught equipment would also be needed.

In a gas mixture, hydrogen expands the range between the lower and upper flammability limits. This increases the danger of light back. In terms of operation, a mixture with hydrogen becomes explosion hazardous in a wider range of concentrations.

The comparison indicates strongly that the conclusion about the possibility of using natural gas/hydrogen mixtures based on the Wobbe index alone is not sufficient. The issues of gas fuel utilization efficiency, environmental performance, and safety require analysis of a wider range of interchangeability indicators.

2. Analysis of interchangeability criteria

The issue of interchangeability of natural gas and its mixture with hydrogen was additionally studied with account for the requirements adopted in the international standard ISO 13686:2013 (International Organization for Standardization, 2013). A list of interchangeability indicators is given in Table 4. Each of them enables analysis of certain adverse effects that may occur at fuel substitution.

Table 4. Interchangeability methods and criteria according to ISO 13686:2013

Method or index	Country	Controlled parameters
Knoy factor	EU	Unit heat rate
Dutton’s criteria	Great Britain, Australia	Flame lift Yellow tipping (sooting) Complete combustion
Weaver method	USA	Complete combustion Flame lift Light back Yellow tipping Unit heat rate Required air excess factor (blasting air consumption)
AGA method	USA	Flame lift Light back Yellow tipping
Delbourg method	France	Yellow tipping. Sooting

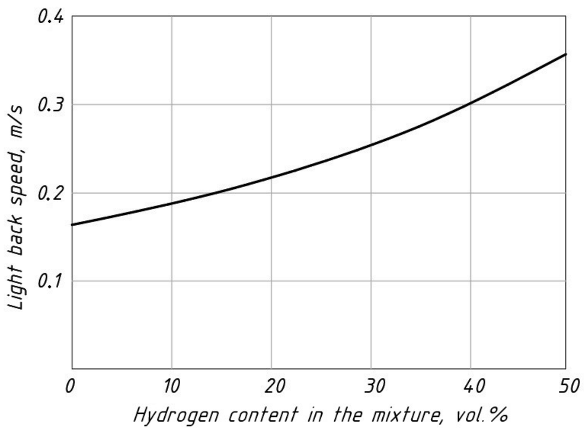

Fig. 5. Maximum gas/air mixture speed at the burner exit when light back is possible

2.1. Knoy factor

The $J_{(K)}$ factor is one of the early interchangeability indices and a variation of the Wobbe index (Briggs, 2014; Knoy, 1953):

$$J_{(K)} = \frac{H_s - 0.65 \cdot 10^7}{\sqrt{\bar{\rho}}}, \quad (2)$$

where H_s — the superior calorific value, J/m^3; $\bar{\rho}$ – the relative gas density.

If the Knoy factor for the substitute gas differs by more than 5%, the gases are not interchangeable. The calculation data show that, in case of natural gas/hydrogen mixtures, it happens with a hydrogen content of more than 20%. With the hydrogen share in the mixture increasing, the unit heat rate will decrease. Therefore, in terms of the Knoy factor, gases with higher hydrogen content are not interchangeable with natural gas.

2.2. Dutton's criteria

Dutton's criteria include the following (Dutton, 1984; Dutton and Wood, 1984; Lander, 2002): $J_{ICF(D)}$ — the incomplete combustion factor, $J_{LI(D)}$ — the lift index, $J_{SI(D)}$ — the soot index.

The **incomplete combustion factor** determines the probability of incomplete combustion products formation when the base gas is replaced with a substitute gas:

$$J_{ICF(D)} = \frac{W_i - 50.73 + 0.03E_{PN}}{1.56} - \frac{\Omega_{H_2}}{100}, \quad (3)$$

W_i — the Wobbe index, MJ/m^3;

E_{PN} — the volume fraction of nitrogen and propane in the stoichiometric mixture, vol.%;

Ω_{H_2} — the volume fraction of hydrogen in the stoichiometric mixture, vol.%.

The Gas Safety Regulations effective in Great Britain require that the value of $J_{ICF(D)}$ be less than 0.48 to prevent incomplete gas combustion. The extreme value of this factor for a substitute gas shall not exceed 1.48. When gases with a higher factor are burned, incomplete combustion products will form and the unit efficiency factor will decrease.

Fig. 6 shows the results of calculations under Eq. (3) for natural gas mixtures with different H_2 content.

According to the calculation data, an increase in hydrogen content does not deteriorate the incomplete combustion factor and is not critical for the mixture, as it is accompanied by a decrease in the hydrocarbon concentration in the mixture. Therefore, in terms of the incomplete combustion factor, natural gas and its mixtures with hydrogen are interchangeable at any hydrogen content.

The **lift index** assesses the possibility of combustible gases interchangeability by the combustion stability criterion — the danger of flame lift and light back phenomena (International Gas Union, BP Gas Marketing Ltd., GL Industrial Services UK Ltd., 2011):

$$J_{LI(D)} = 3.25 - 2.41\arctan\left\{\begin{array}{l}\left(0.122 + 0.0009\Omega_{H_2}\right)\cdot \\ \cdot\left[\left(W_i - 36.8 - 0.0019E_{PN}\right) + \left(0.755 - 0.118E_{PN}^{0.33}\right)\Omega_{H_2}\right]\end{array}\right\}, \quad (4)$$

when $J_{LI(D)} = 0$, there is no visible detachment of the flame base from the burner ports in multi-flame burners. When $J_{LI(D)} = 6$, this means the complete detachment of 50–100% of the flames.

We also analyzed the shift of the index to the region of negative values, not referred to in the publication (International Gas, BP Gas Marketing Ltd., GL Industrial Services UK Ltd., 2011). This would mean the possibility of another critical phenomenon — flame lift with a range of adverse and hazardous consequences.

Fig. 7 shows the results of index calculations for natural gas/hydrogen mixtures under Eq. (4). Evidently, this indicator is not critical for natural gas/hydrogen mixtures within the whole range of hydrogen content under consideration. The deviation of the index value from zero is insignificant.

Dutton's **soot index** assesses the risk of transition from one type of gas to another in terms of danger related to pyrolytic processes of hydrocarbon degradation and formation of soot particles that color the flame yellow (International Gas, BP Gas Marketing Ltd., GL Industrial Services UK Ltd., 2011):

$$J_{SI(D)} = 0.896\arctan\left(\begin{array}{c}0.0255E_{PN} - \\ 0.009\Omega_{H_2} + 0.617\end{array}\right). \quad (5)$$

The limit value of this index is 0.6. A higher value of $J_{SI(D)}$ for a substitute gas means the danger of sooting and limited interchangeability.

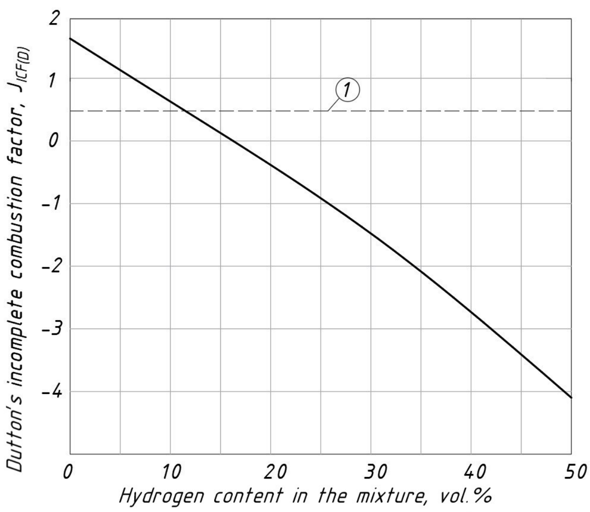

Fig. 6. Dutton's incomplete combustion factor for a natural gas/hydrogen mixture (1 — the normalized value of $J_{ICF(D)} = 0.48$)

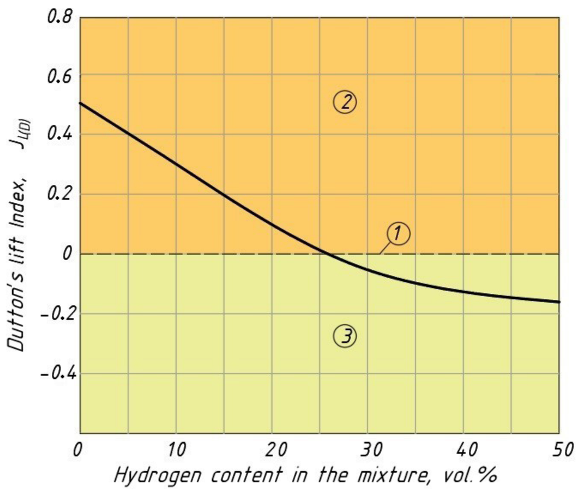

Fig. 7. Dutton's lift index for natural gas/hydrogen mixtures (1 — the limit value; 2 — the flame lift region; 3 — the light back region)

Fig. 8 shows the results of Dutton's soot index calculation for natural gas/hydrogen mixtures. They indicate that the introduction of hydrogen into the mixture does not lead to sooting. Therefore, in terms of this index, natural gas/hydrogen mixtures are interchangeable.

Therefore, according to Dutton's criteria, the substitution of natural gas with its mixture with hydrogen is impossible already at a hydrogen concentration of 20–25 vol.% due to light back and flame out.

2.3. Weaver method

This multi-index method was first published in 1946 and has been continuously revised and updated (American Gas Association, 2002; Weaver, 1951). The method assesses the possibility of gas interchangeability in a wider and complex context. It is based on dozens of thousands of experiments with 500 different gases (Ortíz, 2014). During these experiments, the possibility of low-pressure burners transition to another gas without loss of combustion stability and efficiency was studied.

The method aims to determine a set of gas and combustion process characteristics for the base gas and substitute gas as well as compare indicators with the required values. If the requirement is met, the gases are considered interchangeable by this criterion.

The first three indices have a limit of 1.0.

The **heat rate ratio** is the ratio between the Wobbe index for the substitute gas W_{ss} and the Wobbe index for the adjustment gas W_{sa}:

$$J_{i\,(W)} = \frac{W_{ss}}{W_{sa}}. \quad (6)$$

The condition $J_{H(W)}$ = 1.0 (±5%) is a condition of interchangeability of two gases (Ortíz, 2014). A

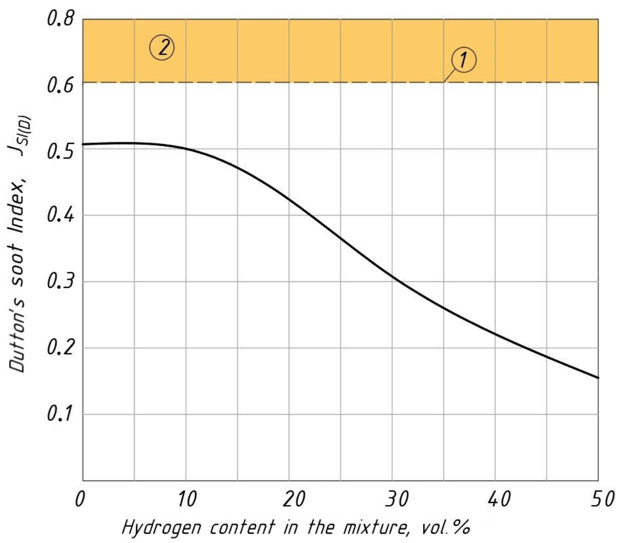

Fig. 8. Dutton's soot index for natural gas/hydrogen mixtures (1 — the limit value; 2 — the sooting region)

higher deviation is considered impermissible by the conditions of changes in the heat rate. Besides, this makes for incomplete combustion, increase in heat losses, efficiency reduction, and loss of combustion stability. Evidently, this condition has been preserved in the majority of the effective standards.

The **primary air ratio** includes theoretical required air for combustion of the adjustment gas V_{ta} and substitute gas V_{ts}, and their relative density, $\overline{\rho}_a$ and $\overline{\rho}_s$, respectively:

$$J_{A(W)} = \frac{V_{ts}\sqrt{\rho_a}}{V_{ta}\sqrt{\rho_s}}. \quad (7)$$

The value of 0.95 < $J_{A(W)}$ < 1.05 is a condition of seamless transition of burners to another gas (Ferguson, 2007). An increase in the upper limit means air shortage, which leads to incomplete combustion, increased emissions of harmful substances, and reduced efficiency of the unit. When the value is less than 0.95, air excess is too high and danger of flame lift occurs, heat losses with exhaust gases increase, the efficiency of the unit decreases, and emissions of toxic nitrogen oxides grow.

The **lifting index** includes the flame speed for the adjustment gas S_a and substitute gas S_s, as well as the volume fraction of oxygen in them, Ω_{O_2a} and Ω_{O_2s} , respectively (Ferguson, 2007):

$$J_{L(W)} = J_{A(W)}\frac{S_s}{S_a}\frac{100-\Omega_{O_2s}}{100-\Omega_{O_2a}}. \quad (8)$$

Substitute gases with a value of $J_{L(W)}$more than 1 are prone to flame lift.

The next three indices are compared by the zero value.

The **flash back index** is calculated by the equation below using the characteristics described above:

$$J_{F(W)} = \frac{S_s}{S_a} - 1.4J_{A(W)} + 0.4. \quad (9)$$

If $J_{F(W)}$ > 0 for the substitute gas, unit operation can be accompanied by light (flash) back, which causes the danger of an emergency (Lander, 2002).

The **yellow tipping index** is calculated using the total content of hydrogen atoms in a molecule of the adjustment gas and substitute gas, N_{Ca} and N_{Cs}, respectively (Halchuk-Harrington and Wilson, 2006):

$$J_{Y(W)} = J_{A(W)} + \frac{N_{Cs}-N_{Ca}}{110} - 1. \quad (10)$$

If $J_{Y(W)}$ > 0 for the substitute gas, it means the possibility of local air shortage, yellow tipping and subsequent sooting.

The **incomplete combustion index** is calculated using the ratio of the number of hydrogen and carbon atoms in molecules of the compared gases, $R_{H/Ca}$ and $R_{H/Cs}$, respectively (Halchuk-Harrington and Wilson, 2006):

$$J_{I(W)} = J_{A(W)} - 0,366\frac{R_{H/Cs}}{R_{H/C\alpha}} - 0.634. \quad (11)$$

If the calculated data for the substitute gas show that $J_{I(W)} > 0$, it means that gas combustion will be accompanied by incomplete combustion and, therefore, reduced unit efficiency and increased emissions of harmful substances. Evidently, this phenomenon can occur both due to a shortage of air for combustion and an increase in the hydrogen content in the substitute gas.

Table 5 shows the results of indices calculations for a natural gas/hydrogen mixture.

Table 5. Comparison of interchangeability indices for natural gas and its mixtures with hydrogen according to the Weaver method

Interchangeability index	Designation	Nominal value (requirement)	Hydrogen concentration in a mixture with natural gas, vol.%			
			0	10	30	50
Heat rate ratio	$J_{H(W)}$	1 (±5%)	1.0	0.95	0.92	0.87
Primary air ratio	$J_{A(W)}$	1 (±5%)	1.0	0.96	0.90	0.83
Lifting index	$J_{L(W)}$	1 (±5%)	1.0	1.12	1.44	1.83
Flash back index	$J_{F(W)}$	≤ 0.0	0.0	0.22	0.73	1.46
Yellow tipping index	$J_{Y(W)}$	≤ 0.0	0.0	–0.04	–0.01	–0.18
Incomplete combustion index	$J_{I(W)}$	≤ 0.0	0.0	–1.2	–1.5	–1.9

The analysis using the Weaver interchangeability method makes it possible to draw the following conclusions concerning the **transition from natural gas to natural gas/hydrogen mixtures** in commercial and domestic gas units. The first four indices give a negative result:

– **in terms of the heat rate ratio**, interchangeability is not achieved when the hydrogen content in the mixture is more than 10 vol.%;

– **in terms of the primary air ratio**, combustion of mixtures, in any case, occurs with increased air excess factors, which will be accompanied by the reduced unit efficiency and danger of flame lift (especially when the hydrogen content in the mixture is more than 20 vol.%);

– **in terms of the lifting index**, any hydrogen content increases the probability of this adverse effect;

– **in terms of the flash back index**, any hydrogen content is also accompanied by the danger of an adverse effect on burners.

It should be noted that the lifting and flash back indices, which are the most negative, were obtained for burners with partial preliminary mixing of gas with air, i.e., for injection burners. Therefore, e.g., for household gas stoves, the result of the analysis using the Weaver method is actually critical. It means that the transition of gas burners from natural gas to natural gas/hydrogen mixtures shall be accompanied by changes in the design of burners, forced-draught equipment, and combustion stabilization devices, as well as changes in burner operation.

As for forced-draught gas burners, flame lift and light back phenomena are not typical for them. The same goes for modern low-power gas boilers with additional flame stabilization, e.g., grid stabilization.

The last two Weaver interchangeability criteria, i.e., the **incomplete combustion index** and the **yellow tipping index**, show that any hydrogen content in a mixture with natural gas does not lead to any phenomena that would deteriorate the combustion process or unit safety.

3. Analysis of interchangeability by heat transfer conditions

All existing interchangeability criteria are related directly to gas burners. However, there is another interchangeability issue that has not been studied yet. It is changes in the nature of heat transfer in boiler furnaces and industrial furnaces during the transition to substitute gases with hydrogen content.

The volume and composition of combustion products change if there is hydrogen in the mixture (Table 3). When the hydrogen content is 30%, the combustion products volume decreases from 11.95 to 7.59 m^3/m^3 with a simultaneous decrease in the content of CO_2 in their composition. Both these factors deteriorate heat transfer in the furnaces of thermal generating units. The first one — due to the reduced rate of combustion products, and the second one — due to the reduced intensity of the radiation heat transfer component.

We studied the combustion of refinery gas with hydrogen content, and the results of the studies indicate that the combustion of gases with a hydrogen content of more than 20% significantly reduces flame radiation and the intensity of convection heat transfer on heating surfaces.

Fig. 9 presents changes in the relative amount of heat received by the water walls of a boiler depending on the hydrogen content in the mixture. Reduction of the radiation heat transfer component in the furnace transfers its significant amount to a less efficient convective section of the boiler. This inevitably increases the temperature of exhaust gases and reduces boiler efficiency.

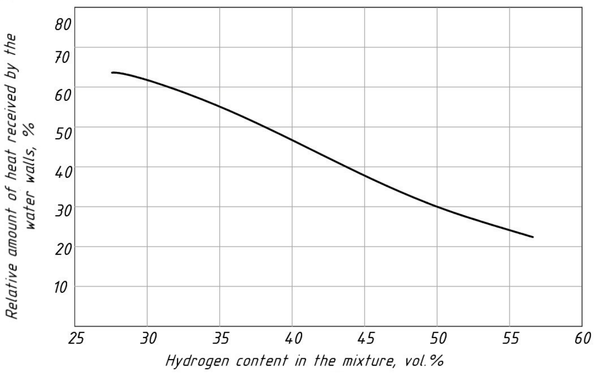

Fig. 9. Impact of the gas composition on heat emission in a furnace

The reason for such a situation is changes in the above ratio of the carbon and hydrogen content in the elemental gas composition, C/H (Mochan et al., 1998). A shift in the C/H ratio to a higher hydrogen fraction reduces the so-called flame “luminosity”, i.e., reduces the yellow (carbon) spectrum component and, therefore, the furnace emissivity.

It should also be noted that the reduction in the stability of injection gas burners operation was confirmed during the studies. With a significant hydrogen content, uncontrolled light back was often observed. It requires immediate intervention of equipment operators in order to avoid an emergency.

Therefore, the use of substitute gases in the form of natural gas/hydrogen mixtures requires an adjustment of the existing method of thermal and aerodynamic analysis of boilers and other heat recovery equipment.

Conclusions

1. The use of natural gas/hydrogen mixtures, including in the domestic sector, is an effective intermediate step in the decarbonization of human activities. This decision makes it possible to ensure the proportionate reduction of CO_2 emissions without changes in the design of gas burners and gas equipment. The main issue in such a transition is permissible hydrogen content in the mixture that would not change the parameters of gas fuel utilization efficiency, environmental performance, and safety.

2. Numerous gas interchangeability criteria are used in different countries. It should be noted that all of them were derived for specific test conditions that are not necessarily applicable to current conditions. For example, the well-known Weaver criteria were derived for the test gas with a superior calorific value of 800 BTU/ft^3 (approx. 29.8 MJ/m^3). Suffice it to say that group E natural gas is characterized by a value of this parameter of more than 1000 BTU/ft^3. Besides, tests are always conducted using certain burners. However, burners of the same type (e.g., injection burners) can have a variety of differences, which leads to different light back and flame lift indicators. The same can be observed in seemingly identical devices. The design accuracy of nozzles and burner ports, their depth and angle, differences in the distance between them — all of this matters. Even slight differences in the material of the device can result in a catalytic or, on the contrary, inhibiting effect on the combustion process.

3. The above requires very careful and responsible application of the interchangeability criteria on a case-by-case basis. Based on the analysis and studies performed, it is safe to say that the use of a natural gas/hydrogen mixture with a hydrogen content of 10 vol.% is permissible for injection burners of household gas stoves and low-power equipment without changes in their design and operation. In a number of cases, a higher hydrogen content (up to 15–20 vol.%) is possible, which, however, requires additional testing.

4. The forced-draught burners of industrial and heating boilers are not prone to light back and flame lift due to the nature of combustion organization. In this case, it is possible to recommend the safe operation of devices using a mixture with a hydrogen content of up to 20–25 vol.%. The same goes for low-power boilers with modern methods of combustion stabilization. However, we should consider accompanying heat rate reduction (up to 15–20%) and assess in advance the technical capability of this phenomenon compensation, e.g., by increasing fuel consumption.

5. The studies performed also allowed us to establish a significant negative impact of adding hydrogen to the mixture on the radiation characteristics of the flame. This should be taken into account (along with heat rate reduction) in heating equipment where radiation heat transfer in the furnace is an important technological component. They, first of all, include boiler units with water-walled furnaces.

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ВЗАИМОЗАМЕНЯЕМОСТЬ И НОРМИРОВАНИЕ ПАРАМЕТРОВ ГОРЮЧИХ ГАЗОВ ПРИ ИСПОЛЬЗОВАНИИ ВОДОРОДА

Александр Леонидович Шкаровский[1,2]*, Анатолий Григорьевич Колиенко[3], Виталий Сергеевич Турченко[3]

[1]Санкт-Петербургский государственный архитектурно-строительный университет
2-ая Красноармейская ул., 4, Санкт-Петербург, Россия
[2]Кошалинский Технологический университет,
ул. Снядецких, 2, Кошалин, Польша
[3]Национальный университет «Полтавская политехника имени Юрия Кондратюка»
Першотравневий проспект, 24, Полтава, Украина

*E-mail: szkarowski@mail.ru

Аннотация

В статье представлены результаты исследований, **целью которых является** обоснование возможности постепенного перехода на сжигание водорода в газоснабжении коммунально-бытовых и промышленных потребителей без необходимости изменения конструкции горелок и режима их работы. Для этого комплексно **рассмотрены задачи** определения показателей взаимозаменяемости природного газа и его смесей с водородом. Исследованы основные характеристики горючего газа при различном содержании водорода в смеси. Определено влияние содержания водорода на показатели тепловой мощности, выход вредных веществ, а также явления проскока и отрыва пламени. Проанализированы известные критерии взаимозаменяемости и их применимость в рассматриваемой задаче использования смесей природного газа с водородом. Впервые рассмотрено влияние содержания водорода на показатели лучистого теплообмена в топках газоиспользующего оборудования. **В основу методологии работы** положен критический анализ имеющихся литературных данных по вопросу взаимозаменяемости горючих газов, а также собственные теоретические и экспериментальные исследования. **Получены зависимости,** которые дают возможность определить возможность перевода имеющегося газового оборудования на сжигание смесей природного газа с водородом. **Разработаны рекомендации** по допустимому содержанию водорода в смеси с природным газом, обеспечивающим эффективное, безопасное и экологичное использование такого топлива в бытовых и промышленно-отопительных устройствах. **Научные и практические результаты работы** дают возможность осуществить малозатратную частичную и постепенную декарбонизацию в области использования газового топлива в качестве промежуточного этапа при переходе к более широкому сжиганию водорода.

Ключевые слова

Газоснабжение, декарбонизация, природный газ, водород, смеси, взаимозаменяемость, допустимое содержание.