PAPER • **OPEN ACCESS**

Interchangeability of various combustible gases and adaptation of gas-using equipment for their efficient combustion

To cite this article: Anatolii Kolienko *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1348** 012048

IOP Conf. Series: Earth and Environmental Science **1348** (2024) 012048 | doi:10.1088/1755-1315/1348/1/012048

Interchangeability of various combustible gases and adaptation of gas-using equipment for their efficient combustion

Anatolii Kolienko[1,3], **Rasul Ahmednabiev**[1], **Oksana Demchenko**[1], **Olha Hukasian**[1], **and Volodymyr Semko**[2]

[1]National University Yuri Kondratyuk Poltava Polytechnic, Pershotravneva St., 24, Poltava, 36011, Ukraine
[2]Poznan University of Technology, plac Marii Skłodowskiej-Curie 5, Poznan, 60-965, Poland

[3]Corresponding author: agkolienko@gmail.com

Abstract. The article presents the results of studies, the purpose of which is to substantiate the possibility of using a wide class of different combustible gases in one gas-using equipment and to develop recommendations for changing the design and operational parameters of such gas-using equipment in the event of a transition from one type of non-interchangeable combustible gases to another. The methodology of the work is based on a critical analysis of the available data on the issue of interchangeability of combustible gases, as well as our own theoretical and experimental studies. Dependencies have been obtained that permit to determine the possibility of switching gas-using equipment from one type of gas to another. Recommendations have been developed on the permissible content of hydrogen in a mixture with natural gas, ensuring the efficient, safe and environmentally friendly use of such fuel in household and industrial heating devices. Scientific and practical results of the work permit to carry out a low-cost reconstruction of gas-using equipment from one gas to another, including the transition to combustible gas containing hydrogen.

1. Introduction

The modern market of combustible gases offers different types of gaseous fuel in terms of composition and characteristics. Among them there are natural gas of various composition, biogas, biomethane, generator gas, liquefied propane gas (LPG), liquefied natural gas (LNG), combustible gases mixed with hydrogen, combustible gas of coal gas seam degassing (mine methane) [1].

According to the current norms [2,3], all types of combustible gases are classified by families (Gas Family), groups (Group) and subgroups. For example, natural gases make up the second family, in which gas with a high methane content belongs to group E. Gases of the same group have similar combustion characteristics and are united by the value of one of interchangeability indices - the Wobbe index, *Wo*, MJ/m^3. The Wobbe index is a complex criterion that includes the combustible physical and chemical characteristics of gases, including their heat of combustion , MJ/m^3 and density ρ, kg/m^3. If the Wobbe index for two different gases differs by more than 5%, then the gases are referred to the category of non-interchangeable and their burning in the same gas-using equipment (GUE) without its reconstruction is impossible [4].

Gas-using equipment, which is produced for the combustion of gases, must be highly versatile and provide the opportunity for the efficient use of the entire variety of combustible gases without fundamental changes in the design of the equipment and its operating modes [9].

In the work studies were carried out aimed at developing justified criteria selecting criteria for the efficient combustion of gases different in composition and properties in one and the same gas-using equipment. To do this, the tasks of research and selection of valid criteria for the interchangeability of various gases, assessment of the influence of the gas's physical and chemical characteristics on the main performance indices of the equipment have been performed.

The problem is relevant in the context of a wide variety of combustible gases in the market, as well as when replacing hydrocarbon fuels with hydrogen-containing mixtures for the purpose of decarbonization, as well as at colliery gas combustion. Assessing interchangeability provides a practical opportunity to answer the question about the permissible content of hydrogen in combustible mixtures. On the one hand, there is a desire to increase the share of hydrogen and obtain the environmental benefits of its use, on the other hand it is ensuring the principles of safety and fuel efficiency, as well as minimizing the investments required to switch gas burners and combustion devices from pure natural gas, for which they were intended, to a mixture of natural gas and hydrogen, or other gas [6,7].

The purpose of the work is to develop recommendations and methods for reconstructing existing gas-using equipment to enable efficient combustion of a wide range of gases with different combustible and physical and chemical characteristics.

2. Methods

The main gas pipelines supply mainly natural gas of group L or E. According to the above requirements [2, 3, 4], the highest Wobbe index for group L gases should have a value of 39.1...44.8 MJ/m^3 (volume is adjusted to the temperature of 15 °C and to the pressure of 1013.25 mbar). The heat of such gas combustion should be 29.3…34.5 MJ/m^3. For group E these values are, respectively, 40.9...54.7 MJ/m^3 and 31.3...44.4 MJ/m^3.

But, according to the standards [4], for the efficient and safe GUE operation, it must be tested by burning not the gases of this group themselves, but the so-called test gases, each of which, in its composition, is critical from the point of view of certain equipment's operation characteristics. Table 1 shows the test gas characteristics for gas groups L and E.

Table 1. Test gas characteristics.

Flammable gas	Test No., test gas composition and characteristics for the following critical equipment operation modes:		
	Light back	Flame lift	Incomplete combustion and "yellow tipping"
Second family group L	G25[1] CH_4 = 86% vol. N_2 = 14 % vol. Wo = 41.52 MJ/m^3 = 32.49 MJ/m^3	G27 CH_4 = 82% vol. N_2 = 18 % vol. Wo = 39.06 MJ/m^3 = 30.98 MJ/m^3	G26 CH_4 = 80% vol. C_3H_8 = 7 % vol. N_2 = 13% vol. Wo = 44.83 MJ/m^3 = 36.91 MJ/m^3
Second family group E	G222 CH_4 = 77% vol. H_2 = 23 % vol. Wo = 4787 MJ/m^3 = 31.86 MJ/m^3	G231 CH_4 = 85% vol. N_2 = 15 % vol. Wo = 4090 MJ/m^3 = 32.11 MJ/m^3	G21 CH_4 = 87% vol. C_3H_8 = 13 % vol. Wo = 5476 MJ/m^3 = 45.28 MJ/m^3

Note: 1- Test gas type designation according to [3].

It is easy to see that the Wobbe index for different test gases differs by more than 5%. Thus, the Wobbe index is not the only criterion for the interchangeability of combustible gases.

Studies of the operation of gas-burning equipment [8,10,14,15] show that when switching from one type of gas fuel to another, or when changing the composition and physical and chemical properties of the same combustible gas, in order to ensure environmental and technical and economic efficiency, the following characteristics of burners and gas-using equipment remain constant:

1. Thermal power of the burner, which is determined by the product of the heat of fuel combustion and its consumption in accordance with the dependence:

$$N = B \cdot Q_{\text{H}}^{\text{P}} = \text{const}, \tag{1}$$

where N – is the thermal power of the burner, kW; B – is the consumption of combustible gas, m^3/s; – is caloric value of gas, kJ/m^3.

The amount of gas consumption B is set based on the operational characteristics of the equipment and is a constant value for a given type of gas. The main influence on the amount of thermal power is the heat of the fuel combustion, which depends on the type and the combustible gas composition. The constancy of the thermal power guarantees compliance with the technological parameters of the equipment.

2. The amount of primary air sucked in by the active gas jet in low and medium pressure injection gas burners. The amount of sucked air must be sufficient to ensure complete fuel combustion with the highest possible efficiency. The injection capacity of the gas jet with a constant burner design and the constant value of the vacuum in the furnace of the unit depends solely on the gas pressure in front of the gas nozzle. This value is determined from the burner's passport or operational data and is constant for a certain operating mode of the burner for a certain type of gas.

When the composition of the gas changes, the amount of air required for complete combustion of the gas must be changed. However, the operational parameters of the equipment declare a constant amount of primary air. And as a consequence, the combustion process of gas, which differs in composition from the passport one, occurs under conditions of air deficiency, a decrease in the efficiency of the unit, and the formation of toxic carbon monoxide in combustion products [6].

3. The total amount of air supplied from fans for combustion of fuel in forced-air burners must also be constant. However, a change in the composition of the combustible gas may leads to a corresponding change in the heat of combustion, and this in its turn leads to the respective change in the amount of combustion caloric value, and this, in its turn, leads to the need to increase or decrease the combustion air flow. Since the operational parameters that determine air flow remain unchanged, combustion of a different composition gas and caloric value of gas in the absence of automatic system, inevitably leads to a decrease in efficiency and deterioration in the environmental characteristics of combustion products.

4. The gas pressure and air pressure in front of the burner must remain stable, whereby a malfunction of the torch occurs, that is, the phenomenon of flame separation or breakthrough. The occurrence of these dangerous processes completely depends on the value of the normal flame propagation speed U, and this, in turn, depends on the composition of the fuel and its physicochemical properties [9].

Thus, for example, an increase in ballast impurities (CO_2, N_2, H_2O) in the gas composition leads to a decrease in the flame propagation speed, a deterioration in the combustible properties of the gas, a narrowing of the stable operation range of the burners, a violation of the flame stability of the burners and a deterioration in their control characteristics [11]. Increasing the proportion of hydrogen in natural gas by more than 20% vol. leads to a significant increase in the burning rate and an increase in the Wobbe index [8]. Therefore, 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% without making changes to the burner's design and its operating mode. An increase in the proportion of oxygen in the mine gas leads to premature flashback of the flame.

The issue of interchangeability of natural gas and other flammable gases was studied taking into account the requirements adopted in the international standards ISO 13686:2015 [1]. The list of interchangeability indices is given in table 2 [12, 11, 12, 13]. Each of them permits to analyze certain undesirable phenomena that are possible when the type of flammable gas is changed.

Table 2. Methods and criteria for interchangeability according to [7-11].

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

3. Results and discussion

According to [2], gases are considered interchangeable without making changes to the operation of burners and the design of fuel-burning equipment, provided that their Wobbe numbers are equal, which characterize the thermal power and aerodynamic parameters of the burners at constant gas pressure and the area of the gas holes.

$$Wo_1 = Wo_2 = \text{const} \ \pm 5\%;$$

$$\frac{Q^{\mathrm{P}}_{\mathrm{H}_1}}{\sqrt{\rho_1}} = \frac{Q^{\mathrm{P}}_{\mathrm{H}_2}}{\sqrt{\rho_2}} = \text{const} \ \pm 5\% \qquad (2)$$

where Wo_1, Wo_2 - are the Wobbe indexes for the first and second gases, respectively; $Q^{\mathrm{P}}_{\mathrm{H}_1}$, $Q^{\mathrm{P}}_{\mathrm{H}_2}$ - heats of combustion for the first and second gases, respectively KJ/m^3; ρ_1, ρ_2 - densities of the first and second gases, respectively, kg/m^3.

Providing a constant thermal power of the GUE for two non-interchangeable gases, for which $Wo_1 \neq Wo_2$ can be achieved by changing the gas flow. And this can only be achieved by changing the area of the firing holes, or the gas pressure. Recalculation of the area when switching from one type of gas to another should be performed according to the dependence obtained by the authors:

- provided that the gas pressure in front of the burner remains constant when switching from one type of gas to another - $P_1 = P_2 = \text{const}$

$$f_2 = f_1 \frac{Q^{\mathrm{P}}_{\mathrm{H}_1}}{Q^{\mathrm{P}}_{H_2}} \left(\frac{\rho_2}{\rho_1}\right)^{1/2}, \qquad (3)$$

where f_1, f_2 are the areas of fire holes or gas nozzles for GUE when operating on the first and second combustible gas, respectively, m^2.

- subject to changes in combustible gas pressure in front of gas-using equipment $P_1 \neq P_2$:

$$f_2 = f_1 \frac{Q^{\mathrm{P}}_{\mathrm{H}_1}}{Q^{\mathrm{P}}_{\mathrm{H}_2}} \left(\frac{\mathrm{P}_1\rho_2}{\mathrm{P}_2\rho_1}\right)^{1/2}. \qquad (4)$$

The diameter of gas holes when switching from one to another non-interchangeable gas at a constant pressure is proposed to be determined according to the following relationship:

$$d_2 = d_1 \left(\frac{Wo_1}{Wo_2} \right)^{1/2}, \tag{5}$$

where d_1, d_2 - are diameters of gas holes for the first and second gases, respectively, mm.

Maintaining the unchanged thermal power of the burner when switching to another gas is possible even if the area of the fire holes and the unchanged design of the burner are preserved. To do this, it is necessary to switch to the other pressure of the combustible gas in front of the burner and change the established operational parameters of its operation.

The gas pressure, which must be set to maintain a constant thermal power when the fuel characteristics change, is calculated according to the dependence proposed by the authors:

$$P_2 = P_1 \frac{\rho_2}{\rho_1} \left(\frac{Q^{\mathrm{P}}_{\mathrm{H}_1}}{Q^{\mathrm{P}}_{H_2}} \right)^2, \tag{6}$$

where P_1, P_2 – is a pressure of gas in front of the burners while working with the first and the second gas, Pa.

The possibility of interchangeability of gases when the gas pressure in front of the burner changes is checked by the equality of the extended Wobbe numbers, which are calculated according to the dependence:

$$Wo_1{}' = Q^{\mathrm{P}}_{\mathrm{H}_1} \left(\frac{\mathrm{P}_1}{\rho_1} \right)^{1/2}, \quad Wo_2{}' = Q^{\mathrm{P}}_{\mathrm{H}_2} \left(\frac{P_2}{\rho_2} \right)^{1/2}, \tag{7}$$

By analogy with the simple Wobbe number (2), two gases are considered interchangeable provided that the expanded Wobbe numbers do not differ by more than 5%:

$$Wo_1{}' = Wo_2{}' = \text{const} \pm 5\%; \tag{8}$$

For injection burners of household gas appliances, it is important not only to ensure constant burner power when switching from one gas to another, but also to observe the conditions under which the required amount of primary air will inject into the burner. In addition, this depends both on the diameter of the burner gas nozzle and on the gas pressure in front of the nozzle. Therefore, when converting an injection burner to another combustible gas for which the interchangeability condition is not met, the nozzle diameter is determined according to the following dependencies:

– under the condition of the known pressure for the new combustible gas:

$$d_2 = d_1 \left(\frac{Q^{\mathrm{P}}_{\mathrm{H}_1}}{Q^{\mathrm{P}}_{\mathrm{H}_2}} \left(\frac{P_1 \rho_2}{P_2 \rho_1} \right)^{1/2} \right)^{1/2}, \tag{9}$$

– under the condition if the necessary pressure for a second combustible gas in front of the burner is unknown:

$$d_2 = d_1 \left(\frac{(1 + \alpha_1 V_{\mathrm{T}1}) \cdot \left(1 + \alpha_1 V_{\mathrm{T}1} \frac{\rho_{\mathrm{a}}}{\rho_1} \right)}{(1 + \alpha_2 V_{\mathrm{T}2}) \cdot \left(1 + \alpha_2 V_{\mathrm{T}2} \frac{\rho_{\mathrm{a}}}{\rho_2} \right)} \right)^{1/2}, \tag{10}$$

IOP Conf. Series: Earth and Environmental Science **1348** (2024) 012048 doi:10.1088/1755-1315/1348/1/012048

where α_1, α_2 - are the coefficients of excess primary air injected into the burner for the first and second combustible gases, respectively (assigned from the condition of preventing the phenomenon of flame breakthrough into the burner mixer); V_{T1}, V_{T2} - are theoretical specific air flow rates required for complete combustion of 1 m^3 of the first and second fuel gases, respectively, m^3/m^3; determined by the condition of preventing the phenomenon of flame breakthrough into the burner mixer); ρ_a =1.29 kg/m^3 - air density under normal conditions.

After determining the nozzle diameter, it is necessary to calculate the gas pressure in front of the nozzle using the proposed dependence:

$$P_2 = P_1 \frac{\rho_2}{\rho_1} \left(\frac{Q^{P}_{H_1}}{Q^{P}_{H_2}} \right)^2 \left(\frac{d_1}{d_2} \right)^4 . \tag{11}$$

The proposed dependencies were tested in the conditions of industrial operation of burners in oil refining industry furnaces, which operate under conditions of continuous changes in the composition of combustible refinery gas.

When the composition of the combustible gas was changed, its pressure in front of the injection burners and the diameters of the nozzles of the burners of the oil refining furnaces were adjusted in accordance with dependencies (10) and (11). At the same time, the constancy of all control parameters of the furnaces was noted: thermal power, the coefficient of performance value, combustion products composition, the absence of visible violations of combustion stability - flame breakthrough and separation. Thus, it was confirmed that changing the gas pressure permits to ensure the combustion of various gases in the same gas burner device.

4. Conclusions

In the work a study of the criteria for the interchangeability of gases and the rules for recalculating the design parameters and operational characteristics of gas-using equipment under conditions of non-interchangeable gases combustion was carried out. Different countries use many criteria for the interchangeability of gases. It should be noted that these are all designed for specific test conditions and do not necessarily apply to current conditions. The above requires extremely careful and responsible use of interchangeability criteria in each specific case.

Combustion of non-interchangeable gases without proper changes in the design of the burners and adjustment of the operating parameters of the unit may lead to a decrease in the control range and disruption of the flame stability of the burners; decreased efficiency of gas use. In this regard, the proposed methods for recalculating the design dimensions and operational characteristics of equipment are important from the point of view of increasing the efficiency of using gaseous fuel, reducing its consumption and reducing the toxicity of combustion products.

Using the results of the research performed to study the possibility of burning hydrogen in the existing gas-using equipment used for combustion of groups L or E gases (natural gas) showed that using a mixture of natural gas with 10% vol. of hydrogen is acceptable for injection burners of household gas stoves and low-power equipment without making design and operating changes.

In the case of using forced-air burners equipped with stabilizing devices, a higher hydrogen content is possible (up to 15...20% vol.), which requires additional research. During such studies, one should take into account the concomitant decrease in the thermal power of devices (up to 15...20%) and study in advance the technical possibilities of compensating for this phenomenon, for example, by increasing fuel consumption.

References

[1] Jones H R N 2005 *The application of combustion principles to domestic gas burner design* (London; New York: Taylor & Francis e-Library) 205 p

[2] International Organization for Standardization 2013 *Natural gas – Quality designation*. ISO 13686:2013 (Geneva: ISO) 48 p
[3] International Organization for Standardization 2013 *Natural gas – Quality designation*. ISO 13686:2013 (Geneva: ISO) 48 p
[4] European Commission 2020 *Communication from the Commission to the European Parliament, the Council the European Economic and Social Committee, and the Committee of the Regions. A hydrogen strategy for a climate-neutral Europe* Brussels, 08.07.2020. COM(2020) 301 final
[5] European Committee for Standardization 2021 *Test gases - Test pressures – Appliance Categories*. EN 437: 2021. Brussels
[6] Flórez-Orrego D A 2011 *Métodos para el estudio de la intercambiabilidad de una mezcla de Gas Natural y Gas Natural-Syngas en quemadores de premezcla de regimen laminar*: Un artículo de revisión 34 p
[7] Gupalo O, Yeromin O, Kabakova L, Kulikov A, Sukhyi M and Romanko Y 2023 Study of the efficiency of using renewable hydrogen in heating equipment to reduce carbon dioxide emissions *IOP Conference Series: Earth and Environmental Science* **1156** 012035. https://doi.org/10.1088/1755-1315/1156/1/012035
[8] Koliienko A, Shkarovskiy A and Turchenko V 2022 Interchangeability and standardization of the Parameters of combustible Gases when using Hydrogen *Architecture and Engineering* **7** (1) pp 33-45. https://doi.org.10.23968/2500-0055-2022-7-1-33-45
[9] International Gas Union. BP International Company. GL Industrial Services UK 2011 *Guidebook to Gas Interchangeability and Gas Quality* 156 p
[10] Knoy F 1941 Combustion Experiments with Liquefied Petroleum Gases. *Gas.* **17** pp 14-19
[11] Lander D 2002 UK situation regarding gas quality. Present to Marcogaz Gas Qual. WG 28th June 2002
[12] Ortíz J M 2014 Fundamentos de la Intercambiabilidad del Gas Natural *Met & Flu Ciencia - Tecnologia-Innovacion* (9) pp 6-15
[13] Delbourg P and Lafon J 1971 *Interchangeabilité des Gaz* (Paris: Association Technique de L'Industrie du Gaz En France) 200 p
[14] Dutton B C 1984 A New Dimension to Gas Interchangeability. Communication 1246, *The Institute of Gas Engineers, 50th Autumn Meeting*
[15] Weaver E R 1951 Formulas and graphs for representing the inter-changeability of fuel gases. *J. res. Nat. Bur. Standards* **46** pp 213-245