JUSTIFICATION OF MEASURES TO IMPROVE STABILITY OF GAS DISTRIBUTION NETWORKS

Yurii Franchuk, Viktoriia Konovaliuk, Mykhailo Kyrychenko, Oleksandr Liubarets
Kyiv National University of Construction and Architecture, Ukraine
franchuk.yy@knuba.edu.ua, coppoca@gmail.com, kirichenko-m@ukr.net, liubarets.op@knuba.edu.ua

Abstract. During the operation of gas distribution networks, there have been changes in concentrated loads, gas flow intensity, and the values of the standard pressure in front of the burners of appliances. The internal cross-section of gas pipelines has decreased, and internal stresses have arisen. The current regulatory framework has significantly increased the requirements for gas quality, composition and supply parameters. Currently, gas supply systems are considering the possibility of transporting gas mixtures with the addition of biomethane or hydrogen to natural gas. The physical and chemical characteristics of mixtures of natural gas with hydrogen of various concentrations are being studied. To meet the established regulatory requirements for gas quality, in particular, for the calorific value, the hydrogen concentration in the mixture should not exceed 7%. In this case, the pressure before the burners of gas appliances must be increased by 4%. The efficiency of using household gas appliances, depending on the gas pressure on the burners, was studied. Measures have been proposed to modernize gas supply networks. For example, ensuring optimal pressure in front of any gas device by the nominal pressure specified in the device passport. Recalculation of the system throughput is based on the higher calorific value of gas. It is recommended to ensure optimum pressure by placing gas-reducing devices as close to the consumer as possible and then adjusting the pressure with gas stabilisers. An important aspect is the cost of gas and the environmental impact of its combustion products. To ensure stable operation of the pressure regulator equipment, an alternative way to increase the gas temperature without burning is proposed. The use of the Rank-Hilsh effect is suggested. This will reduce gas consumption and avoid open flames, which will increase operational safety and reduce emissions of pollutants into the atmosphere.

Keywords: gas supply, nominal pressure, gas volume, pipe diameter, pressure loss.

Introduction

The vast majority of Eastern European gas networks were built in the last decades of the last century. They were designed for gas flows and loads that were relevant at the time. Gas appliances worked efficiently under those conditions. Nowadays, the load and intensity of gas flows, the regulatory conditions for ensuring stable operation of gas appliances, and the composition of gas have changed significantly. Over several decades of operation of gas networks, gas pipelines have become clogged, their internal cross-section has decreased, and internal stresses have arisen in many places. Most gas networks have been operating beyond their service life (25 years).

Scientists and practitioners from different countries are dealing with the urgent issue of improving the efficiency of the gas supply system. The regulatory framework of the European Union is aimed at increasing the level of energy saving and energy efficiency of engineering systems, the main provisions are set out in [1] Directive 2012/27/EU of the European Parliament and of the Council on Energy Efficiency.

The main component of gas transported in gas supply networks is methane. Methane is a non-renewable energy source with limited reserves. The transition to renewable energy sources is now a topical issue. There is a transition from the outdated gas market system, which uses only fossil fuels, to a new model that provides for a competitive environment, wider use of renewable energy sources and modernization of existing energy supply systems. Researchers from different countries have proposed using renewable energy sources to replace fossil fuels. In the case of natural gas, it is proposed to use mixtures with biogas, synthesis gas, ammonia, hydrogen, and various process gases. Paper [2] describes the transition of the global energy system from fossil fuels to hydrogen. The environmental benefits of hydrogen combustion are presented.

In the article [3], hydrogen is considered as a means of storing renewable energy. Blending hydrogen with the existing gas pipeline network has been proposed as a means of increasing the performance of renewable energy systems. Provided that relatively low concentrations of less than 5-15% hydrogen by volume are used, such a strategy for storing and supplying renewable energy to markets seems viable without significantly increasing risks. Articles [4; 5] note that biogas can replace natural gas if it is purified to the level of green gas. Article [6] analyzes the problems that arise when transporting a mixture of gas and hydrogen in gas transmission networks. It is noted that due to the effect of hydrogen embrittlement, the compatibility of pipeline steels and associated welds with hydrogen is a serious problem when designing hydrogen-carrying pipelines.

Paper [7] investigated the explosion protection characteristics of mixtures of natural gas and hydrogen. The mixtures become more "critical" in terms of explosiveness with an increase in the hydrogen fraction. However, the dependence of safety characteristics on the hydrogen fraction is generally not linear. Adding up to 10% hydrogen to natural gas has almost no effect on safety characteristics. A more significant impact on safety characteristics was observed at a hydrogen content of more than 25%. Paper [8] discusses the prospects of using mixtures of natural gas and hydrogen as an alternative fuel. According to [9], Germany has started supplying hydrogen to the gas network and plans to increase its concentration to 20%. Paper [10] notes that hydrogen admixture in natural gas changes the properties of fuel gas. The negative impact of hydrogen admixture is mitigated by increasing the excess air ratio. However, conventional combustion control technologies may not be able to respond to the presence of hydrogen in the fuel.

Ukraine is also considering the possibility of producing hydrogen for domestic consumption and transportation to European countries. Proposals to inject hydrogen (H_2) from renewable sources into the natural gas system are economically attractive. In particular, the electrolysis of water with electricity generated from wind, solar, etc. is a promising area. The results of the study [11] indicate that in some parts of the natural gas system it is possible to add up to 10% hydrogen by volume to natural gas.

One of the ways to reduce the use of natural gas is to reduce its consumption for its own needs, including when servicing gas supply system facilities and more efficient combustion in gas-consuming appliances. Thus, in the dissertation [12], it is substantiated that using the method of frictional heating of natural gas in energy separators instead of its direct combustion at gas distribution stations can save up to 300 thousand m3 of natural gas per year.

Therefore, taking into account the requirements of the time to improve the efficiency of gas networks, the requirements for the use of secondary and renewable resources, and based on the results of research by scientists in the field of gas supply, there is a need to increase the stability of the required pressure before gas appliances, the ability of gas appliances to operate in conditions of gas networks being supplied with alternative fuel, hydrogen.

Paper [13] analyses the change in the thermal power Q of a gas burner device in relation to Q nom depending on the gas pressure. Thus, when supplying a gas pressure of 1000 Pa with a nominal pressure of 1800 Pa, the burner power decreases to 70.7%. The analysis of scientific research [14] shows that in the construction of gas supply systems, the cheapest system is a single-stage medium gas pressure system using polyethylene pipes and the installation of house pressure regulators.

The dependence of the ratio of the power of a burner at a certain gas pressure to its power at the nominal gas pressure on the gas pressure before the burner (Fig. 1) was researched in [13]. However, the research gives no information about gas consumption.

The scientific novelty of the work lies in the experimental study of the dependence of gas consumption on the pressure in front of the burners of a household gas stove to determine the optimal gas pressure. The work aims to minimize the consumption of natural gas by ensuring the gas pressure in front of the burners equal to the optimal value according to the results of experimental studies, as well as to avoid burning natural gas to compensate for its cooling in pressure reducers and partial replacement with hydrogen.

Materials and methods

To determine the dependence of the gas flow rate on the pressure in front of the burners of a household gas stove to determine the optimal gas pressure, an experiment was set up (Fig. 2). The research was announced in the works [15-17] but was not finished. The study was carried out in the gas supply system that supplies gas to Yampil and Mokrovolia villages in the Khmelnytsky region of Ukraine, which are fed from the Bilogirya and Yampil gas distribution stations.

To determine the optimal gas pressure, we studied the efficiency of gas combustion in a household gas stove at variable gas pressure. According to the supplier's data [15], gas was supplied to Yampil with the following parameters: weighted average lower combustion heat 34.66 $MJ \cdot m^{-3}$, weighted average higher combustion heat 38.36 MJ·m^{-3}, methane content 89.1%, ethane content 5.1%, propane content 1.3%.

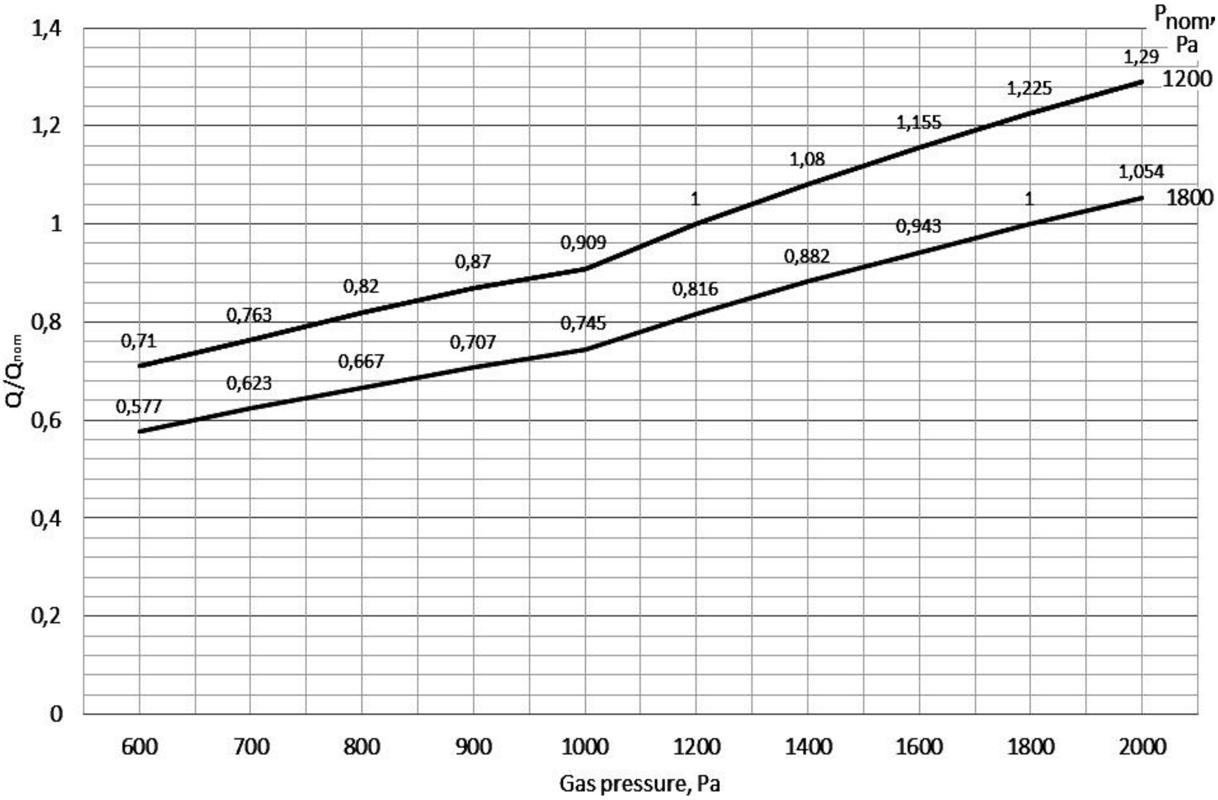

Fig. 1. **Dependence of the burner power ratio at a certain gas pressure *Q* to its capacity at the nominal gas pressure Q_{nom} from the gas pressure at different nominal pressures of gas burners P_{nom}**

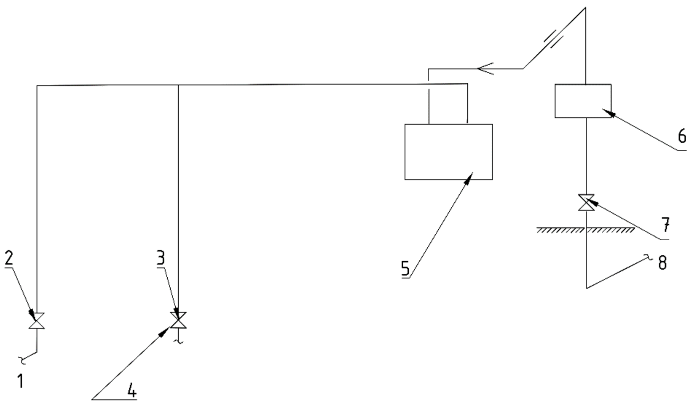

Fig.2. **Experimental setup:** 1 – connection point of the gas stove for the test at different pressures; 2 – gas valve ⌀ 15 mm; 3 – gas valve ⌀ 15 mm for the measuring device; 4 – connection point of the manometer; 5 – gas meter; 6 – gas pressure regulator; 7 – main valve; 8 – pipeline of average gas pressure of 0.3 MPa

The pressure in the street gas pipeline near the building where the experiments were conducted was 0.28 MPa. Throttling was carried out using the RDGS-10 regulator installed on the wall of the gasified building.

The efficiency of the burners of a Gefest gas stove PG-4 with an operating pressure of 2000 Pa indicated in the device passport was determined. A Samgas G4 membrane gas meter, certified according to the established procedure, was used for gas metering. The stove has four burners: one of high, two of normal and one of low power.

The experiments were performed for four inlet pressure conditions (1800, 2000, 2400, and 2600 Pa) on the high- and normal-power burners.

The process of heating water in a vessel with a volume of $V = 3$ dm^3 was studied. The initial water temperature was $T_1 = 303.15$ K, and the atmospheric pressure was 98 257 Pa. The water was heated until it boiled. Gas consumption was determined as the difference in the meter readings at the end and beginning of water heating.

The permissible amount of hydrogen is determined according to the admissible lower heating value LHV_{adm}, MJ·m^{-3}, according to the Gas Transmission System Code using the formula for the lower heating value of each component LHV_i, MJ·m^{-3}, with the corresponding amount r_i:

$$r_{H_2} = \frac{LHV_{adm}}{\sum_{i=1}^{n} LHV_i \cdot r_i}. \tag{1}$$

Results and discussion

The experimental study of the impact of pressure changes on the efficiency of household gas appliances in the existing gas supply system gives the results in Fig. 3.

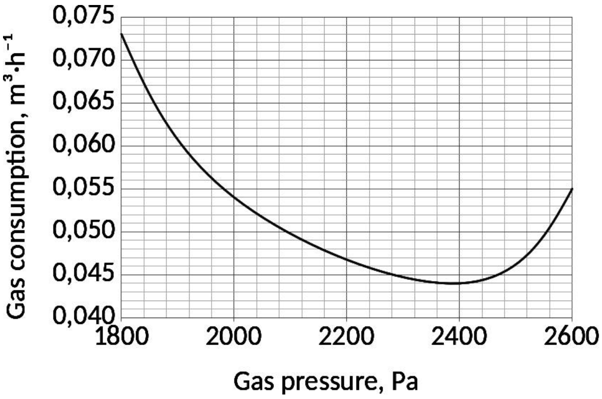

Fig. 3. **Graph of gas flow versus pressure**

At the optimum pressure of 2400 Pa, the gas consumption is 0.044 m^3·h^{-1}. If the pressure is increased by 200 Pa or decreased by 420 Pa, the gas consumption will increase to 0.055 m^3·h^{-1} – by 25%. Thus, focusing only on the standard pressure ranges [18-19] dependent on the nominal pressure (Fig. 4) leads to gas overconsumption. Reduced efficiency leads to an increase in the volume of incomplete combustion products, which are highly toxic to humans and more dangerous for the environment than greenhouse gases.

The current DBN "Gas Supply" recommends calculating gas pressure at a gas pressure of 1200 Pa at the burners [20]. At the same time, the analysis of the requirements of the passports of the manufacturers of the equipment used provides for different pressures of 1200...1300 Pa, 1800 Pa, 2000 Pa, 2500 Pa.

In multi-storey buildings, we have a parallel connection of gas appliances from different manufacturers with different optimal pressure values. For buildings with more than 4 storeys, the pressure will change due to gravity, and the overall pressure loss along the length. Which of these components will prevail depends on the characteristics of the gas supply facility and the instantaneous gas supply regime. It is impossible to set the optimum pressure for all gas appliances even when using a house pressure regulator.

Therefore, it is suggested to install pressure stabilisers in front of each gas appliance. The practice of apartment stabilisation is used in the electricity supply systems of developed countries but is not used in gas supply. Taking into account that the optimum pressure in front of the burners is 2400 Pa and when gas is supplied from the regulator to the burners, pressure losses occur at the meter, it is recommended to set the setting pressure of RDGS-10 at 2400 Pa plus pressure loss. This optimisation should be combined with the replacement of some natural gas by green hydrogen.

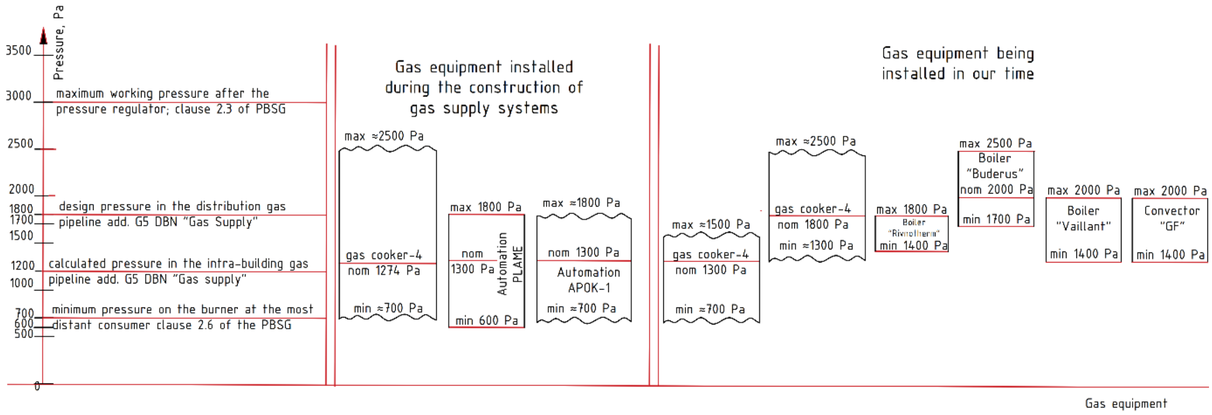

Fig. 4. **Gas pressure distribution in the gas pipeline from the gas regulator station to the consumer, gas pressure requirements for gas consuming devices**

An analysis of the cost of construction and installation works of a gas supply system for the settlement was carried out. The most economically feasible option is a single-stage medium gas pressure system using polyethylene pipes and installing house pressure regulators in each dwelling. If we assume the cost of such a system to be 100%, the cost of a similar system made of steel pipes is approximately 136%, and of two-stage systems with steel pipes 164%, and polyethylene pipes – 125%. In other words, even two-stage systems using polyethylene pipes are cheaper than one-stage systems with steel gas pipelines. A single-stage medium gas pressure system using polyethylene pipes and the installation of house gas pressure regulators is also the cheapest in terms of specific indicators of the construction of gas distribution networks in a settlement [14].

The composition and quality of the gas supplied is of great importance. Gas quality is determined by the Gas Transmission System Code, Gas Distribution System Code and the Technical Regulations for Natural Gas. However, this Code only establishes the characteristics of gas that is allowed for transportation, but not for use by consumers.

By the law of Ukraine [21], the capacity distribution is recalculated by the coefficient corresponding to the higher heating value, which is 38.3 MJ·m^{-3} (10.64 kWh·m^{-3}). When calculating the distribution part of the gas supply system, DBN [20] recommends using a heating value of 34 MJ·m^{-3}. We consider it necessary to recommend using a higher heating value of 38.3 MJ·m^{-3} (10.64 kWh·m^{-3}) when determining the diameters of gas pipelines.

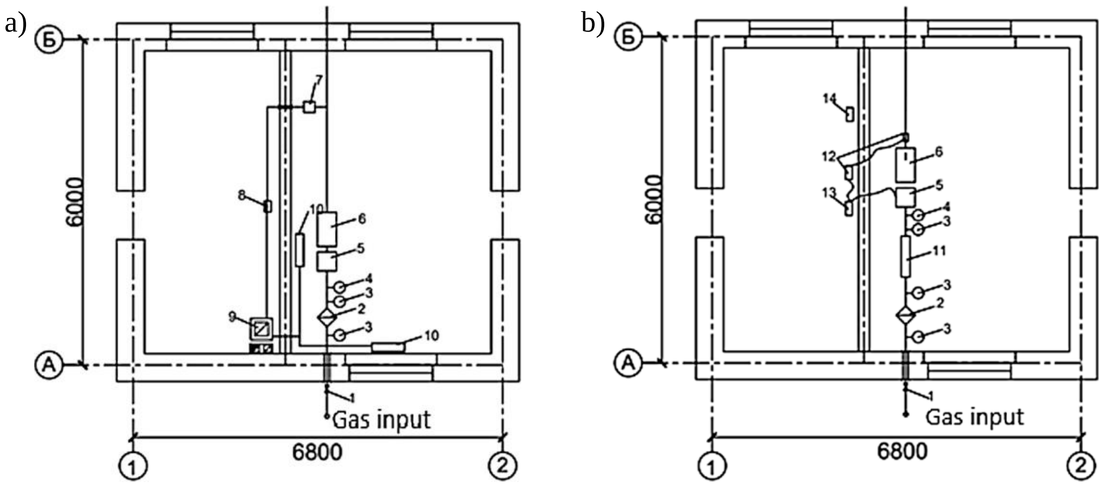

Fig. 5. **Typical design of a hydraulic fracturing unit:** a – before changes; b – with proposed changes. 1 – gate valve; 2 – filter; 3 – pressure sensor; 4 – temperature sensor; 5 – gas metering unit; 6 – pressure regulator; 7 – RDGS–10; 8 – G-4 meter; 9 – boiler; 10 – heater; 11 – gas heater; 12 – chromatograph; 13 – secondary converter; 14 – GSM/GPRS/VPN communication channel

Gas quality changes during transporting because of water inflows during intensive precipitation through walls and welding of old pipes with micro-defects, condensing of heavy hydrocarbons, chemical reactions with pipe material of aggressive components (for example, sulphurous compounds), etc. Thus, we need to measure the heating value of each consumer (Fig. 5).

When the natural gas pressure at the fracturing station decreases, the Joule-Thomson effect, i.e. a decrease in the gas temperature is observed. If the temperature in the room is below 5-8 ºC, liquid fractions are formed in the gas and crystallohydrates of CH_4-$7H_2O$ can form.

To ensure stable operation of the hydraulic fracturing system, the gas temperature must be maintained at a certain level during throttling. The gas temperature must exceed the condensation temperature of the individual gas fractions. In this case, it is important to ensure only the gas temperature since the air temperature in the fracturing room does not directly affect the process.

We propose to maintain the temperature of the gas which pressure is reduced at the gas distribution station using a device that works according to the Rank-Hilsh effect [21-24].

This device will reduce the gas consumption for heating in the gas-distributing plants building by about 450 m^3 of gas per month, which is about 3000 m^3 during the heating period [25].

The use of gas for heating incurs certain financial costs, open flames in the fracturing room are dangerous, and combustion products are released during gas combustion, which harms the environment.

The use of liquefied gas, hydrogen or biogas will help balance the load. The use of liquefied gas will ensure the autonomy of these gas consumption facilities and will provide a certain economic effect [2-4]. Thus, when using liquefied gas, the consumer has the opportunity to purchase gas at the time of its lowest price and use it for a certain period, regardless of limits, prices, possible outages, etc.

The regulatory requirements for hydrogen content in gas networks in different countries are analysed as shown in [8] Table 1.

Table 1

Maximum permissible hydrogen concentration in gas networks

Country	Netherlands	Germany	France	Spain	Austria	Switzerland
$H_{2,\ \%}$ob	12	10	6	5	4	4
Country	Italy	Sweden	Belgium	United Kingdom	Japan	Ukraine
$H_{2,\ \%}$ob	3	0.5	0.1	0.1	0	undetermined

We calculated the permissible hydrogen content in the gas mixture to be transported in the Ukrainian gas transmission system, subject to the standard values of the calorific value according to the Gas Transmission System Code. Fig. 6 shows the effect of hydrogen content on the volumetric heat of combustion.

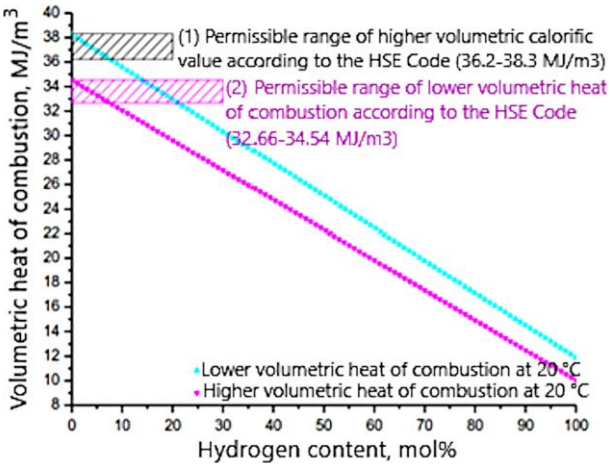

Fig. 6. **Changes in the volumetric heat of combustion of natural gas with increasing hydrogen H_2 content**

Based on the quantitative and qualitative composition of natural gas typical for the city of Kyiv, theoretical calculations of changes in the physicochemical properties of a mixture of natural gas and hydrogen were carried out. It was found that the density and volumetric heat of combustion decrease in direct proportion to the increase in hydrogen concentration. To meet the Wobbe interchangeability criterion of 5% deviation, the hydrogen content should not exceed 19 mol.%. To meet the requirements for the volumetric heat of combustion set by the Ukrainian legislation, the hydrogen content by equation (1) must be within 7 mol.%. Thus, the limiting factor for the hydrogen content of gas is the calorific value.

To maintain a constant power output of gas burners in household appliances, the pressure in the gas distribution network needs to be increased by about 4%. This is not a burden for a low-pressure gas distribution network.

With a hydrogen content of 7 molecular per cent, the upper limit of ignition of a gas-air mixture will increase slightly, while the lower limit will remain virtually unchanged. To ensure the safe operation of gas networks, localisation and elimination of gas leaks, existing safety measures will have to be improved or even new ones developed.

The issue of the impact of the natural gas-hydrogen mixture on the construction materials of gas networks and the economic justification remains relevant and requires further study.

The analysis of the gas network operation points to certain shortcomings that reduce its efficiency. We propose measures that will improve the operation of gas networks, namely: to calculate new and recalculate existing networks using all the energy of the gas, i.e. the higher heat of combustion along the gas route; for new gas networks, to use mainly polyethylene pipes with a maximum supply of high (medium) pressure to the consumer. This will ensure that the required pressure is supplied to the burners of gas appliances, maintains the required gas temperature before the regulator due to the Rank-Hilsh effect without burning gas for heating, makes greater use of biogas and hydrogen in gas networks, carries out gas metering in energy units.

The proposed changes in gas supply systems will result in a reduction of gas pipeline diameters due to full utilisation of gas energy; more accurate gas metering in volume units and energy units during transportation and the ability to monitor gas flows with forecasting for the future, the ability to determine gas losses by analysing energy flows, the use of the Rank-Hilsh effect will result in certain gas savings, improvement of the environment by avoiding gas flaring to heat the hydraulic fracturing facility, rational use of medium and low-pressure gas networks, ensuring and maintaining the required gas parameters before the burners of gas appliances, ensuring actual metering of energy consumption; wider use of renewable and secondary energy resources.

Overall, the proposed measures will reduce the volume of gas consumed and ensure reliable energy supply to consumers.

Conclusions

Experimental studies have shown a significant impact of the gas pressure on the efficiency of gas stoves. For example, for a Gefest PG-4 stove, the gas consumption at the optimum pressure of 2400 Pa is 0.044 $m^3 \cdot h^{-1}$. If the pressure is increased by 200 Pa, the gas consumption will increase to 0.055 $m^3 \cdot h^{-1}$, and if the pressure is reduced by the same amount, the increase will be up to 0.0467 $m^3 \cdot h^{-1}$. Since this value depends on the model and manufacturer, it is necessary to stabilize the pressure before each consumer. The gas heating value should be measured for each consumer because the gas quality changes during transportation. The gas burning to compensate for the gas cooling due to pressure reduction should be replaced with a Rank-Hilsh effect gas heater. Due to the shortage of gas in Ukraine, it is advisable to mix hydrogen with it in an amount of up to 7%. It is recommended to use hydrogen from renewable sources or electricity at energy consumption gaps.

Author contributions

Conceptualization, Y.F.; methodology, V.K.; formal analysis, M.K.; investigation, O.L., writing – original draft preparation, V.K.; writing – review and editing, Y.F.; project administration, M.K.; funding acquisition, Y.F. All authors have read and agreed to the published version of the manuscript.

References

[1] Директива Європейського Парламенту і Ради 2012/27ЄС від 25 жовтня 2012 року про енергоефективність, внесення змін … (Directive 2012/27/EU of the European Parliament and of

the Council of 25 October 2012 on energy efficiency, amending ...) (In Ukrainian). [online] [19.03.2024]. Available at: https://zakon.rada.gov.ua/laws/show/984_017-12#Text

[2] Momirlan M, Veziroglu T. The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. Int J Hydrogen Energy, vol. 30, 2005, pp. 795-802. DOI: 10.1016/j.ijhydene.2004.10.011

[3] Melaina M., Antonia O., Penev M. Blending hydrogen into natural gas pipeline networks: a review of key issues, 2013, Contract 303:275-3000. DOI: 10.2172/1068610.

[4] Hengeveld E., W.J.T. van Gemert, Bekkering J., Broekhuis A. When does decentralized production of biogas and centralized upgrading and injection into the natural gas grid make sense?, Biomass and bioenergy, vol. 67, 2014, pp. 363-371. DOI: 10.1016/j.biombioe.2014.05.017

[5] Dolci F., Thomas D., Hilliard S. et al. Incentives and legal barriers for power-to-hydrogen pathways: an international snapshot. International Journal of Hydrogen Energy, vol. 44, 2019, pp.11394-11401. DOI: 10.1016/j.ijhydene.2019.03.045

[6] Wang H., Tong Z., Zhou G. et al. Research and demonstration on hydrogen compatibility of pipelines: a review of current status and challenges, International journal of hydrogen energy, vol. 47, 2022, pp. 28585-28604. DOI: 10.1016/j.ijhydene.2022.06.158

[7] Askar E., Schröder V., Schütz S., Seemann A., Power-to-Gas: Safety Characteristics of Hydrogen/Natural- Gas Mixtures, Chemical Engineering Transactions, vol. 48, 2016, pp. 397-402.

[8] Mayrhofer M., Koller M., Seemann P. et al. Assessment of natural gas/hydrogen blends as an alternative fuel for industrial heat treatment furnaces. International journal of hydrogen energy, vol. 46 (41), 2021, pp. 21672-21686. DOI: 10.1016/j.ijhydene.2021.03.228

[9] Hydrogen Central, "E.ON, Avacon and DVGW announce 20 percent hydrogen in the German gas network for the first time" [online] [11.02.2024] Available at: https://hydrogencentral.com/eon-avacon-dvgw-20-percent-hvdrogen-german-gas-network/

[10] Leicher J., Schaffert J., Cigarida H. The impact of hydrogen admixture into natural gas on residential and commercial gas appliances, Energies, vol. 15, 2022, 777 p. DOI: 10.3390/en15030777

[11] Altfeld K. and Pinchbeck D. Admissible hydrogen concentrations in natural gas systems, gas for energy, vol. 3, 2013, pp. 36-47. [online] [11.02.2024] Available at: https://www.gerg.eu/wp-content/uploads/2019/10/HIPS_Final-Report.pdf

[12] Савченко О. Фрикційне нагрівання природного газу в енергетичному роздільнику (Frictional heating of natural gas in an energy separator) : PhD thesis ... Candidate of Technical Sciences: 05.23.03/Savchenko O.O.: Ministry of Education and Science of Ukraine, Kyiv National University of Construction and Architecture - Kyiv, 2008. p. 24. (In Ukrainian). [online] [11.02.2024] Available at: https://nrat.ukrintei.ua/searchdoc/0408U001086/

[13] К. Аналіз фізико-хімічних показників властивостей природніх газів (Analysis of physical and chemical indicators of the properties of natural gases)/Urban planning and territorial planning - 2018. - pp. 532-539. (In Ukrainian). [online] [11.02.2024] Available at: https://repositary.knuba.edu.ua/handle/987654321/6629

[14] Предун К., Рибачов С., Ахоніна А. Техніко-економічне порівняння систем газопостачання населених пунктів (Technical and economic comparison of gas supply systems of settlements), Ventyliatsiia, osvitlennia ta teplohazopostachannia, iss. 14, 2010, pp. 147-150 (In Ukrainian). Available at: http://nbuv.gov.ua/UJRN/votp_2010_14_22

[15] Предун К., Коновалюк В., Франчук Ю. Аналіз впливу тиску газу на параметри його спалювання в побутових газових плитах (Analysis of the influence of gas pressure on the parameters of its combustion in household gas stoves). Ventyliatsiia, osvitlennia ta teplohazopostachannia, vol. 38, 2021, pp. 51-56 (In Ukrainian) DOI: 10.32347/2409-2606.2021.38.47-54

[16] Коновалюк В., Франчук Ю. Підвищення ефективності використання природного газу в побутових газових плитах (Increasing the efficiency of the use of natural gas in household gas stoves) Ventyliatsiia, osvitlennia ta teplohazopostachannia, vol. 43, 2022, pp. 31-37 (In Ukrainian) DOI: 10.32347/2409-2606.2022.43.31-37

[17] Коновалюк В., Франчук Ю. Дослідження проблеми забезпечення оптимального тиску в розподільних мережах газопостачання перед побутовими газовими приладами (Study of the problem of ensuring optimal pressure in gas distribution networks in front of household gas

appliances), Ventyliatsiia, osvitlennia ta teplohazopostachannia, vol. 33, 2020, pp. 32-37 (In Ukrainian) DOI: 10.32347/2409-2606.2020.0.32-38
[18] NPAOP 0.00-1.76-15. Правила безпеки систем газопостачання (Safety rules for gas supply systems). - K.: Osnova, 2015. - 179 p. (In Ukrainian) [online] [11.02.2024] Available at: https://masterpechnik.com/wp-content/uploads/2016/09/npaop_0_00-1_76-15.pdf
[19] Технічний регламент природного газу (Technical Regulations for Natural Gas), Cabinet of Ministers of Ukraine [Electronic resource]. 2019. - 61 p. (In Ukrainian) [online] [11.02.2024] Available at: https://www.drs.gov.ua/wp-content/uploads/2021/07/dokument-7033_0_19-21.pdf
[20] V.2.5-20-2018. Газопостачання (Gas supply), Ministry of Regional Development of Ukraine. - K.: Ministry of Regional Development of Ukraine, 2019. - 109 p. (In Ukrainian) [online] [11.02.2024] Available at: https://dreamdim.ua/wp-content/uploads/2019/04/DBN-V2520-18_Gas.pdf
[21] Law of Ukraine Про внесення змін до деяких законів України щодо запровадження на ринку природного газу обліку та розрахунків за обсягом газу в одиницях енергії щодо терміну набрання чинності (On Amendments to Certain Laws of Ukraine on the Introduction of Metering and Settlements for Gas Volumes in Energy Units in the Natural Gas Market Regarding the Effective Date)/Verkhovna Rada of Ukraine [Electronic resource]. - 2022. - 1 p. (In Ukrainian) [online] [11.02.2024] Available at: https://zakon.rada.gov.ua/laws/show/1850-20#Text
[22] Xue Y., Arjomandi M., Kelso R. Experimental study of the thermal separation in a vortex tube, Experimental Thermal and Fluid Science, vol. 46, 2013, pp. 175-182. DOI: 10.1016/j.expthermflusci.2012.12.009
[23] Eiamsa-ard S., Promvonge P. Review of Ranque-Hilsch effects in vortex tubes, Renewable and Sustainable Energy Reviews, vol. 12, 2008, pp. 1822-1842. DOI: 10.1016/j.rser.2007.03.006
[24] Xue Y., Arjomandi M. The effect of vortex angle on the efficiency of the Ranque- Hilsch vortex tube, Experimental Thermal and Fluid Science, vol. 33, 2008, pp. 54-57. DOI: 10.1016/j.expthermflusci.2008.07.001
[25] Франчук Ю., Пефтєва І. Енергоефективний підхід до підігріву і обліку газу в стаціонарних ГРП системи газопостачання України (Energy-efficient approach to gas heating and metering in stationary gas distribution stations of the gas supply system of Ukraine). The scientific heritage. vol. 114 (114), 2023, pp. 52-56 (In Ukrainian) [online] [11.02.2024] Available at: https://www.calameo.com/read/00505976990013a3f91d2