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MIXED FUEL FOR HOUSEHOLD GAS-POWERED APPLIANCES AS AN OPTION TO REPLACE NATURAL GAS WITH HYDROGEN

Introduction. *In the opinion of world expert association, the global warming of boundary layer within the system of "Earth's surface — ambient atmospheric air" has been caused by the effect of carbon-containing components (mainly CO_2) referred to as greenhouse gas (along with H_2O) and by the redistribution of radiative heat fluxes within the environment.*

Problem Statement. *The principal sectors of economics influencing upon the greenhouse gas emission include an industry, electric and heat power generation, means of transport. However, in the Ukrainian conditions, the municipal and household gas supplying sector is of special significance given the structure and the main constituents of the national fuel balance, particularly in the case where a reduction in CO_2 emissions is attained by carbohydrate fuel substitution with hydrogen.*

Purpose. *The purpose of this research is to determine the opportunities for safe operation conditions and the prospects for natural gas substitution with hydrogen by supplying household gas-powered appliances (HGA) with mixed fuel and to experimentally study the feasibility (efficiency) and HGA environmental characteristics (harmful gas CO and NOx emissions).*

Materials and Methods. *The problem of environment decarbonization nowadays has been solved by substitution the natural gas (NG) with NG (methane) blended with hydrogen. The household gas devices: RÖDA heating boiler (Germany) and GRETA gas cooker stove (Ukraine) have been tested in terms of combustion of the MG (air mix containing up to 50% (vol.) [H_2]) as compared with pure NG.*

Results. *The moderate impact of [H_2] content in fuel gas in terms of power and environmental characteristics of HGA by varying the [H_2] fraction within the range of [H_2] = 0—50% (vol.) has been stated.*

Conclusions. *For the first time, the theoretically predicted possibility of safe operation of HGA with the use of methane-hydrogen mixes with [H_2] content up to 50% has been experimentally proved. The boiler efficiency in terms of fuel consumption grows with increasing heat capacity, in contrast to the extreme dependence of the gas stove efficiency on heat capacity.*

Keywords: atmospheric burner, efficiency of fuel use, environmental characteristics of flue gases, gas cooker, heating boiler, hydrogen as alternative fuel, interchangeability of fuel gases, laminar burning velocity.

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One of the problems caused by the global climate change is the need to fight for the decarbonization of environment by means of substitution the coal and the carbon-containing fuels. In the current period of sustainable development, it makes an impressive effect on power engineering technologies.

The most pressing problems associated with the use of fuel are related to environmental pollution because of the formation of harmful effluents (nitrogen oxides, carbon monoxide, unburned hydrocarbons UHC, and PM10, PM2.5 particles).

Many countries have introduced national (*Germany*) and /or international (*European Union*) strategies relevant for the obligations to reduce greenhouse gases effluents till 2030 and 2050 within the framework of the Paris climate agreement [1—2] and the European Green Deal (11.12.2019) [3]. The use of hydrogen meets the requirements for decarbonization of environment in the best way.

1. Hydrogen is distinguished by enhanced flammability characterized by a high laminar burning velocity S_L [4] as well as by an ultra-low time of ignition (self-ignition, autoignition) or ignition delay time τ_{ign} [5]. Moreover, the hydrogen ignition causes a huge explosion danger: the methane number of H_2 makes MN = 0 that means minimum stability of given fuel to detonation in comparison with methane (according to the definition of MN and proper value).

The formation of fire-damp (detonating) gas — stoichiometric mix of H_2 with an oxygen ($2H_2 + O_2$) that burns under ignition — serves as an indicator of extreme flammability of hydrogen and of the need for undertaking special safeguard measures.

For this reason, the firing/explosion problems shall be identified and addressed at the stage of process and design solutions of fuel supply.

Besides this, the use of hydrogen complicates the operation of equipment and strengthens the requirements to the pipelines and to the control system. High cost of hydrogen, which many times exceeds the natural gas price, is an additional problem associated with the use of H_2-containing fuels.

Given the mentioned reasons, the use of mixed methane (natural gas (NG))+hydrogen gas fuel is considered a compromise approach. The most important aspect of this solution is to find the optimal composition of mixed fuel and to determine the share of hydrogen in mixed fuel.

The hydrogen chosen for mixed fuel gas shall meet the requirements for "green" origin. It means that using the carbon containing components shall be excluded or minimized and the conditions of proper hydrogen production shall be revised accordingly. The use of water electrolysis for H_2 production is the main way for supplying the power systems with "green" energy.

The numerous climate controlling documents deal with the "green" hydrogen production, storage, distribution, and utilization. The national, EU and international laws and regulations as well as bilateral and multilateral agreements have been approved to advance the benign future [6—8].

The European Commission has prepared two strategies in the energy area, which aim at the implementation of the hydrogen technologies. The "hydrogen" strategy assumes the decarbonization of environment in industry, power generation, household appliances, and transport.

Like other European countries, Germany has made an option for "green" hydrogen fuel [6], while Ukraine is going to supply H_2 by means of existing pipelines in accordance with bilateral political and R&D cooperation agreements of the recent period [6, 7].

2. Recently, hydrogen has been considered one of the most suitable types of fuels, an alternative to fossil fuels for supplying combustion chambers of turbines and furnaces with renewable energy. At the same time, H_2 is considered a means for generating power the whole year round, day and night. Some ways could be considered under condition of accumulation of electricity generated by renewables. Excess power could be used to produce hydrogen by the electrolysis method and its storage for later use and redistribution in time and space [9].

Hydrogen-related technologies provide an opportunity to support the sustainable operation of power systems due to the redistribution of energy supply in time (during seasons and 24 hours) and in space (in different geographical and climate zones) by means of underground facilities "when wind does not blow and the sun does not shine" [9], which means a non-effective state of both mentioned constituents of "green" energy.

3. In this research, the problem of using the methane-hydrogen mixes in comparison with the natural gas as a fuel for the operation of household gas-powered appliances (heating boiler and cooker stove) has been discussed. Atmospheric burners (AB) have been considered universal common burner type for household gas-powered appliances. Since these AB facilities belong to the premixed type burners, the combustion instability occurs much more frequently than in the case of non-premixed industrial burners.

There is a bigu difference in the combustion processes in industrial furnaces and power boilers, on the one hand, and in household gas-powered appliances, on the other hand. This difference shall be taken in account for the implementation of hydrogen technologies and for the consideration of the use of H_2 as a fuel. The mentioned difference is caused both by

- different ranges of used heat capacity of the burners: middle and high fuel flow rate, for the industrial equipment, and low flow rate, for the household facilities;
- different types of burners used: the non-premixed fuel and air-oxidant flows (burners without any premixing including FLOX burners of flameless oxidation type), for the industrial application [1, 10, 11], and the premixed atmospheric burners, for the household devices [12].

4. This research presents the results of testing the household gas equipment with the premixed atmospheric burners in terms of the power and environmental characteristics of combustion of CH_4/H_2 mixes at a hydrogen concentration ranging $[H_2]$ = 0—50% (vol.). These tests have been done for varying $[H_2]$ concentration, including at a concentration that exceeds the maximum concentration $[H_2]_{max}$ that has been studied before.

At the same time, in the case of using the hydrogen for heating the industrial plants, $[H_2]_{max}$ is higher (60—70% (vol.)) than the mentioned maximum for the household appliances (50%).

In ferrous metallurgy, when the non-premixed burners are used in the furnaces with the application of proper technologies, $[H_2]_{max}$ reaches 100% (clean hydrogen). The relevant information has been obtained and given by companies by *Tenova* (Italy and Germany), *Hybrit* (Sweden), *Walter Dreizler GmbH* (Germany). due to the achievements of 2020—2021. and the suppliers of branded equipment to China and Russian Federation [11].

5. The composition of alternative mixed gas (MG) that is a mix of NG or methane with hydrogen depends on the principles of combustion process and the burning equipment to be used.

The classification of MG has been proposed by the Gas Technology Institute (GTI, Des Planes, USA) [1]. In the case of H_2 share in the mix with NG (methane): $[H_2] < 10\%$, the MG is called low-hydrogen fuel gas. If $10 \le [H_2] \le 30\%$ (vol.), the MG fuel is referred to medium-hydrogen fuel gas; if $[H_2] > 30\%$ (vol.), the MG belongs to the high-hydrogen fuels.

THE PRESENT-DAY STATUS OF THE PROBLEM

The phenomenon of environment decarbonization has been a central focus of society because of its influence upon warming the atmosphere. Research and engineering expert groups all over the world have been considering the carbonization problem in the context of progress in power engineering and the political activity in the sphere of climate and support of sustainable development of power engineering.

As a consequence of the mentioned considerations, the numerous studies and developments related to the implementation of the hydrogen technologies in the world economy have been made recently in many scientifically advanced and

[1] Webinar GTI Tech Talk: Road to Zero: Low Carbon Energy Systems — The Role of Hydrogen, April 13, 2021 — GTI.

industrially developed countries of Europe (EU) [13]. The similar tendencies have been observed in the leading countries of other continents: North America, Russia, China, and Japan [14].

As it pointed out by the Gas Technology Institute (GTI, USA) [2], for the purpose of studying, hydrogen is considered an alternative energy carrier by "achieving net zero goals (as to greenhouse effluence) across the entire value chain, from production and generation to end use, and offers great opportunities to decarbonize our energy system as well as a sizable portion of our economy".

1. In the United States, due to the efforts of Department of Energy (DOE), several research centers, especially GTI [14] have carried out R&D works and considered the idea of using the mixed fuel by injection of hydrogen into natural gas network.

2. Typically, a threshold value of H_2 concentration is 10% (vol.); some regulations put limitations upon H_2 concentration in the gas mix [15]:

- for underground gas storages in porous rocks: not defined;
- for steel tanks in cars operating on natural gas: 2% (vol.);
- for gas engines, the threshold H_2 concentration is 2% (vol.). Higher concentrations up to 10% are possible for the conditions of separately studied engines with specially designed control systems, given the methane number of the gas mix;
- for gas turbines of the most advanced designs, there is a limit of $[H_2] \leq 1\%$ despite a fairly simple upgrade for the use of $[H_2]$ concentration up to 5% and even 15%.

3. The use of hydrogen as a component added to fossil fuels, primarily, natural gas is envisaged in European countries, in particular in Germany, as a means for the decarbonization of the atmosphere and the reduction of the impact on global climate change by reducing CO_2 emissions from combustion products. By this approach, H_2 is considered a "green hydrogen" that is obtained with the use of environment friendly (green, renewable) energy (solar, wind).

In Germany [15], the systematic R&D works aiming at creating the designs of gas mixers for various purposes and engineering solutions for supplying H_2 in to natural gas pipelines have been carried out; the limits for adding hydrogen to natural gas supplied to the gas networks have been under consideration.

Mixing a small amount of hydrogen (up to 10%) into natural gas pipelines shall be ensured by engineering solutions based on the considerations of economic feasibility and, above all, the safety of relevant systems for gas storage, transportation, and use. Given these positions, the European Union has supported relevant projects in the past decade.

4. The energy community tends to reconsider outdated ideas on impossibility of using hydrogen in heating systems. In 2019, *AVACON AG* (Germany) has launched a pilot project. The essence of the project that has been implemented in Sachsen-Anhalt is to increase the share of hydrogen added to the gas distribution network up to 20%. The project is expected to be realized jointly by AVACON and Deutscher Verein des Gas- und Wasserfaches (DVGW) as a model for the future use of H_2 in the gas supply and distribution system [16].

5. At present, the leader in the practical use of hydrogen for the energy sector is the UK, where considerable experience and data on the implementation of hydrogen as a fuel, including the *Energy Monitor* publication, have been analyzed [17, 18]. The project has been implemented as 30 buildings in the Keele University campus and 100 houses in Staffordshire were heated with a mix of natural gas and hydrogen [17]. Hydrogen obtained by electrolysis of water has a share of 20% (vol.) in the fuel mix [17, 18]. From the source of H_2, the hydrogen flow is fed further into the pipes of the distribution network. The innovative component of the project was preceded by laboratory tests of the gas appliances.

[2] Webinar GTI Tech Talk: Meeting the demand for low-carbon hydrogen resources, November 9, 2021 – GTI.

It has been assumed that all household gas appliances that were purchased after 1996 should comply with the national and European standards given the safety conditions and the requirements for guaranteed properties of design materials. It means the ability to maintain the operation of the gas supply system on a fuel containing 23% H_2. Fuel gas G222 with a similar chemical composition ($[CH_4]$ = 77%, $[H_2]$ = 23%) appears in GOST R 50696—2006 [19] as a limit gas for flame flashback. Great attention has been paid to this project in view of the further use of mixed gas (methane with hydrogen), including the energy generation for transport purposes and heavy industry. The project is planned as a pilot one for 10 months and for the subsequent use of the results in 670 residential and commercial facilities [18].

Another example of using hydrogen is the pilot project for heating 300 houses, which is supposed to be implemented in the UK in the system of Scottish gas distribution networks (SGN) [18].

Our project aims at determining the characteristics of blended fuels with a higher hydrogen concentration, which provides decarbonization of environment while reducing other harmful effluents and emission of greenhouse gases without decreasing the fuel utilization efficiency. We have made experimental studies of gas equipment in order to optimize the flue gases composition by burning selected fuel gas, in terms of compliance with the requirements of relevant Ukrainian and European environment standards.

6. The development of a new fuel — *hythane* — methane—hydrogen mix (*MHM*) with a content of $[H_2]$ from 20 to 44—48% has excited a considerable interest [20]. There are 2 fundamentally different types of technologies for obtaining *MHM and its production*:

- by mixing natural gas with hydrogen produced by electrolysis of water;
- by AMC (adiabatic methane conversion) technology [20] that is realized without extraneous energy carriers; natural gas serves as raw materials, the combustion products of natural gas play the role of energy source.

Hythane is expected to be used in gas turbines, for power engineering, transport, and industrial technologies.

Along with the optimistic approach developed by Western European companies and research centers, the doubts regarding availability of using the “green” hydrogen, in particular, for large-scale heating of buildings have become widespread.

7. Despite a significant number of pilot projects to replace fossil fuels with hydrogen using existing gas distribution infrastructure and even the existence of a standard (UK) on the possibility of using the water—fired boilers, some calculations have been made to justify the economic inexpediency of using the hydrogen as a fuel in some modern industries.

The production of “green” hydrogen by electrolysis is very expensive. It is assumed that the cost of 1 kilowatt hour for production of H_2 will amount to EUR 0.1, in 2030.

For example, heating a space with “green” hydrogen requires 5 times more wind and / or solar energy than that with the help of an efficient heating pump for heat or electrification purpose. In addition, support for the operation of old gas pipeline mains (in the UK) needs to be justified and is questionable (see *Energy Monitor* analysis) [21].

Determining the Recommended Compositions of Methane–Hydrogen Fuel Gas

The most important problem of the use of methane—hydrogen fuel is optimal ratio of the components: the intention to increase the hydrogen content in the mixed gas, on the one hand, and the safety requirements for fuel use from standpoint of flammability, on the other hand. To determine the range of the characteristics for blended fuels by researches and to identify the experimental tests of gas equipment to be done, it is necessary to quantify the anticipated dangerous properties of methane–hydrogen mixes for given content of H_2.

For measuring the combustible and explosive (detonation) properties of the tested fuel–oxidizer mixes the theory of combustion and explosion, namely laminar burning velocity S_L (LBV) known as the rate of normal flame propagation shall be considered [22].

The combustion rate S_L depends on the composition of fuel and oxidizer, excess air coefficient λ and fuel equivalence ratio φ (in the case of an air as an oxidizer, $\varphi = \lambda^{-1}$), and the process parameters: pressure p and temperature T.

Figure 1 shows the dependence of maximum LBV — $S_{L,max}$ on excess air coefficient $\lambda = \lambda_{max}$, $S_{L,max} = f(\lambda)$. The fuel composition is defined by the content of hydrogen in the mix with methane. Other characteristics of the process are the ratio of volumes (masses) of oxidant and air, mode characteristics: standard (or almost standard): pressure p_0 = 1 atm. (0.101325 MPa); T = 300 K ≈ T_0.

The fuel-oxidizer mixes characterized by condition $S_L = S_{L,max}$ are considered from the standpoint of excess air coefficient λ_{max} for fuels of arbitrary composition (in this case, methane–hydrogen gases of a given ratio [CH_4]: [H_2]). It means $S_L(\lambda_{max}) > S_L(\lambda \in \lambda_{max})$.

Table 1. **Increase in LBV $S_{L,max}$ and Excess Air Coefficient λ_{max} in the Case of the Combustion of Methane-Hydrogen Fuel with Air as Oxidant**

#	[H_2]; % vol.	$S_{L,max}$, cm/s	λ_{max}	$S_{L,max}([H_2])/S^{basic}_{L,max}$	Increase $S_{L,max}$ as compared with the reference, % rel.
1 (reference)	0	39.2	0.95	1.0	0
2	5	40.6	0.94	1.036	3.6
3	10	42.0	0.94	1.071	7.1
4	20	45.4	0.94	1.158	15.8
5	30	49. 8	0.93	1.269	26.9
6	50	63.8	0.91	1.627	62.7
7	60	75.8	0.89	1.934	93.4
8	70	94.6	0.87	2.413	141.3
9	90	187.3	0.76	4.778	377.8
10	100	308.1	0.60	7.857	685.7

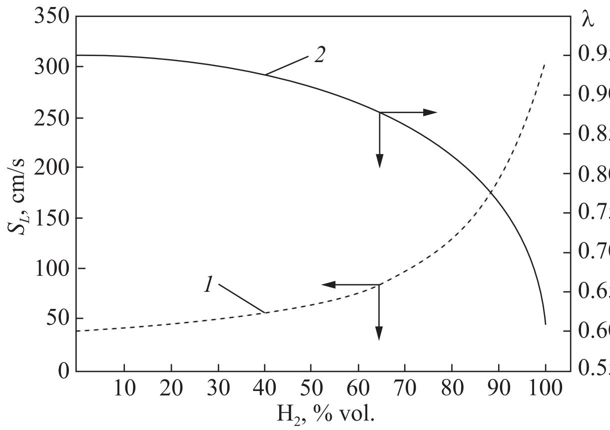

Fig. 1. Dependences of maximum laminar burning velocity (LBV) $S_{L,max}$ (curve *1*) and excess air ratio λ_{max} (curve *2*) corresponding to the maximum LBV of MHM under the conditions of gas combustion in air on the content of [H_2] in the mixed gas. The left ordinate corresponds to $S_{L,max}$ (for chosen H_2 concentrations in the mixed gas), while the right ordinate corresponds to λ_{max} for respective H_2 concentration

The analysis of the presented data has shown a rather smooth and slow dependence of $S_{L,max}$ on the hydrogen content in the mixed gas within the concentration range [H_2] from 0 % to 50% (vol.) followed by a sudden increase in S_L in general and in $S_{L,max}$ in particular, at any rate, within the range of [H_2] ⊂ {70; 100%}.

The obtained dependence of S_L([H_2]) (on hydrogen concentration) indicates the feasibility of limiting of safeguard content of [H_2] in the case of increase in the [H_2] concentration up to 50% and a little bit more.

While considering the feasibility of hydrogen admixing to methane (natural gas), the estimates have been obtained by means by calculating S_L for combustion mechanism GRI 3.0 [23].

The results of our original calculations are presented in Fig. 1 and in Table 1 in the form of dependences of maximum velocities of laminar combustion of the studied mixed fuels with an air for the case of (compositions and flow rate ratios) $S_L = S_{L,max}$. At the same Figure, the proper values of excess air coefficient λ_{max} for each composition of mixed fuel CH_4—H_2 are demonstrated.

Maximum burning velocities with an air as an oxidant $S_{L,max}$ for mixed CH_4—H_2 fuels as compared with those for pure methane have been calculated. In the case of $[CH_4]$: $[H_2]$ = 50/50% (vol.), $S_{L,max}$ increases by 62.7% (up to $S_{L,max}$ = = 0.91 m/s), while in the case of pure hydrogen ($[H_2]$ = 100%, $[CH_4]$ = 0), the maximum value of LBV adds 685.7%, and reaches $S_{L,max}$ = 3.081 m/s (Table 1).

Energy Efficiency and Emissions of Harmful Substances from Combustion of Methane–Hydrogen Mix / Discussion of the Results

The following household gas appliances (household gas devices) have been selected for testing and studying of heating with the use of hydrogen–methane mixes:

- *GRETA* gas stove equipped with the atmospheric burners of different heat capacity;
- household double–circuit boiler "MICRA DUO CS 24" manufactured by *RÖDA*.

The tests are done with the use of the equipment and the gas supplying systems arranged within the proven ground of Chernyakhiv section of *Zhytomyrgaz* (Ukraine).

The gas-powered appliances have been tested based upon the above presented results of theoretical studies in which methane–hydrogen mixes with the content of $[H_2]$ = 0—50% (vol.) were used as a fuel. The experimental tests have been carried out by combustion the fuels of the following composition: the natural gas NG (without hydrogen) and the mixed gases MG with $[CH_4]/[H_2]$ ratio, % vol.: 95/5; 90/10; 80/20; 70/30; and 50/50.

The objectives of the experimental studies are as follows:

- ***determining the possibility of*** using the conventional household appliances (gas stoves, boilers, water heaters, etc.) on hydrogen mixes as fuel gas. To this end, the existing gas networks and equipment of premises and buildings should be tested with the use of mixed gas;
- ***establishing the range of*** rational permissible hydrogen content $[H_2]$ in the mixed gas on the basis of experimental and industrial tests of the gas equipment;
- ***limiting*** $[H_2]$ concentration value in the mixed gas fuel, which corresponds to the regulations for fuel from the standpoint of safety, technological, power-engineering, and environmental restrictions.

Energy efficiency of gas appliances

1. Because of using the atmospheric ejection burners for heating the household gas-powered appliances (HGA) only two operation parameters are considered the control actions: fuel flow rate and heat capacity of appliance. The mentioned values are linearly interdependent. Another independent parameter of the process, which serves as an argument for analyzing the power and environmental characteristics of combustion process in HGA, is the quantitative composition of fuel (in % vol.)

2. Two types of HGA supplied with atmospheric burners could be considered in terms of one more additional operation parameter, an effective air excess ratio (coefficient) l_f:

- *in the case of cooker stoves:* the l values, primary l_{pr} and current l pattern of the two-stage burner's flame within an open space are *invariable* with respect to heat capacity;
- *in the case of fuel combustion in the heating boilers or gas water heaters* equipped with the combustion chambers and flue channels essentially limited by the walls. The ejection of primary and secondary constituents of working process is *varied* depending on heat load. The self-similarity of the ejection process is broken down and the air excess ratios change.

3. Usually the dependences of efficiency η_f of the thermal units or devices on thermal power are of extremal character and have an optimum parameter(s). As the fuel flow rate grows, the efficiency increases under a low output capacity of the thermal units (heat appliances), when the share of heat losses is dominant in the heat balance. After reaching the maximum efficiency (optimum point) and further, an increase in the thermal capacity of the unit (appliance) leads to a gradual decrease in the efficiency of the unit.

It has been stated that the similar extremal dependences of efficiency of "gas burner of *NORD* cooker stove — heat–receiving water vessel" system are observed in our laboratory experiments in the Gas Institute when firing the appliance with natural gas [24], as well as in the field tests of the similar system when burning the methane-hydrogen mixes with the use of atmospheric burners of *GRETA* gas stove within the range of hydrogen concentration $[H_2]$ = 0—50% (Fig. 2).

The dependence of the efficiency of fuel use in GRETA gas stove (Fig. 2) has a typical extremal character with a maximum efficiency that significantly decreases (in a wide range of heat capacities), as the stove output power (the fuel consumption) grows. Increasing the share of $[H_2]$ fraction in the fuel leads to a rise in the efficiency of the cooker stove up to 59% as regulated by DSTU [25].

4. The low-pressure ejection burners for gas cooker stoves are used in the conditions of unlimited air space of double–staged combustion process. In fact, the constant (invariable) coefficient(s) of excess air λ are maintained in this case by variation of output power (thermal capacity of the burner) [26]. Under these conditions, a fixed composition of combustion products (CP) shall be determined depending on λ pattern within the combustion space corresponding to primary air excess $\lambda_{pr} \approx$ const. The harmful substances (toxic components in the CP (the pollutants)) are formed at concentrations $[X_p] \equiv [CO]$, $[NO]$, $[NO_2]$ depending on the type of fuel, air ratio, and fuel flow rate V_f [27].

5. Unlike in the case of the atmospheric burners of gas stoves with a free access of the secondary air to the combustion space, when the air flows are practically proportional to the gas flow, for *RÖDA* boiler with the special channels for the air flow, an insignificant increase in the air flow rate by adjusting the output through the boiler thermal capacity has been reported. It means a decrease in the total coefficient of air excess λ_b in the system of the preparation of combustible mix and the formation of exhaust combustion products in the case of increased gas fuel flow rate (consumption). This leads to a rise in the effective combustion temperature (in the case of normal operation $\lambda_b \rightarrow 1.0$ for "lean" (with $\lambda_b > 1.0$) gas mix). The mentioned conditions are kept in the whole boiler pathway, including the outlet section of the working space and / or the combustion products (flue gases) path of the boiler. Thus, an increase in the thermal power of *RÖDA* boiler (as a result of increasing fuel consumption) leads to decreasing excess air coefficient, while the draught of flue gases in the channels and in the combustion chamber is reduced and so does the respective ejecting capacity of the atmospheric burners.

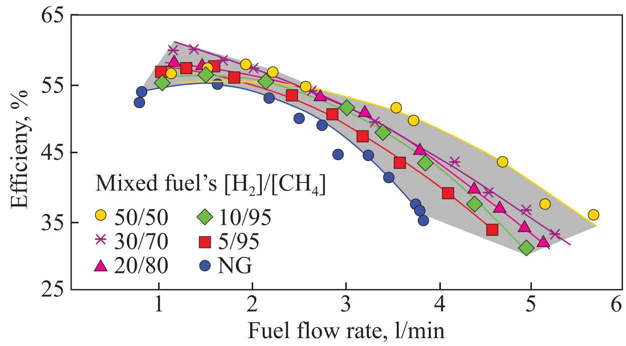

Fig. 2. Dependence of efficiency (%) on the fuel flow rate (consumption), *l*/min for *GRETA* gas cooker. Volumetric concentration hydrogen to methane ratios, $[H_2]/[CH_4]$, % vol., in the mixed fuel are shown in the graph

Testing of the boiler in terms of firing conditions has showed that as the fuel flow rate increases, so do the initial temperature of the combustion products and the absolute value of heat losses with the products flow. Nevertheless, the boiler's efficiency increases due to growing fuel flow rate and the thermal power of the boiler (Fig. 3), since the relative share of the heat losses from the flue gases as the component of the heat balance of the boiler goes down. That is, the decisive factor for the operation of *RÖDA* boiler, in terms of the effect on the boiler efficiency, is the excess air coefficient λ_b in the working space and the flue. The mentioned factor increases with a growth in the boiler heat capacity. A decrease in λ_b leads to an outpacing increase in the useful heat Q_{use}, *a*s compared with the growth of heat Q_{in}.

As a result of the fuel combustion processes and of heat and mass transfer, the efficiency η_f ***of RÖDA boiler*** increases from 85 to 91.5% due to growing fuel flow rate, in the case of the use of NG as a fuel. When replacing the fuel with a mix $[CH_4]/[H_2]$ = 50/50%, the corresponding efficiency ranges within 82—88% (Fig. 3).

6. To estimate the accuracy of measured η_f, the relative mean error of η_f determination shall be calculated.

For this purpose, let us use estimate the relative error $\delta_{\eta f}$ as a sum of relative errors of δQ_{use} ($\dot{Q}_{use}$) and δQ_{in} ($\dot{Q}_{in}$).

The efficiency of boiler is calculated by the formula:

$$\eta_f = Q_{use} / Q_{in} = (\dot{Q}_{use}) / \dot{V} Q_{f,l}.$$

Within the framework of this approach, the final result is

$$\Delta\eta_f = \eta_f \delta\eta_f = \eta_f (\delta \dot{Q}_{use} + \delta\dot{Q}_{in}).$$

The averaged value for the results of the *RÖDA* boiler tests is $\overline{\eta}_f$ = 85%.

The maximum absolute error Δ for η_f value, given the accuracy of the gas meter (≈3%) and the heat meter (≈1.5%), makes up about 5%:

$$\Delta\eta_f \approx 5\%,$$

$$\eta_f = \tilde{\eta}_f \pm \Delta\eta_f = \tilde{\eta}_f (1 \pm \delta\eta_f).$$

Thus *RÖDA* boiler efficiency: η_f = 85 (1 ± 0.05) = = 80.8%—89.3%.

7. Despite the improving radiation properties of combustion product flux, in the case of using methane-hydrogen gas mixes as fuel, the *RÖDA* boiler efficiency is lower for CH_4 —H_2 mixes as compared with pure natural gas, at least, in the case where the share of hydrogen in the fuel and the share of steam in the combustion air (and, accordingly, the share of steam in the combustion products) increase.

The difference in efficiencies h_f for a boiler operating on various types of fuel has been determined depending on the fuel composition and hydrogen content. As the share of hydrogen in CH_4—H_2 mix gas increases, the *RÖDA* boiler efficiency in terms of fuel consumption h_f decreases.

Influence of fuel composition on the formation of harmful emissions

1. Harmful emissions from the RÖDA boiler. The measured concentrations of pollutants decrease to 3% O_2 and are determined in course of the firing tests. An adverse effect of fuel flow rate (consumption) $\dot{V}_f$ regarding the formation of major air pollutants in the combustion products (an increase in [CO] concentration) has been observed. The following results have been obtained concerning nitrogen (NO_X) and carbon (CO) oxides (Fig. 4, *a, b*):

— *for [CO]: for increasing fuel flow rate* $\dot{V}_f$*, an extremal effect* with a significant lowering of [CO] concentration to a minimum, at $[CO]_{3\%\ O2}$ = 10—25 ppm, has been reported for hydrogen content $[H_2]$ = 30—50% (vol.) in the fuel gas. At the same time, $[CO]_{3\%\ O2}$ = 50—70 ppm for pure NG or for mixed gas with $[CH_4]$ content up to 90—95%;

— *for* $[NO_X]$*: a tendency towards increasing the* NO_X *emissions from the boiler as the fuel flow rate increases has been obtained, based upon the generalization of the experimental results*. It means that there are opposite trends in respect of [CO] and $[NO_X]$ formation when the fuel flow rate varies. The largest emissions of $[NO_X]_{3\%O2}$ from the boiler based on maximum consumption of the compared fuels have been found. The maximum $[NO_X]$ emissions amount to near 80 ppm, practically regardless of the content of H_2 in the mixed fuel. At the same time, the $[NO_X]_{3\%O2}$ concentration at low and middle fuel flow rates is the minimum value for 50/50% (vol.) methane- hydrogen mixed fuel.

2. Environmental effect of the atmospheric burners of gas stoves (Fig. 5, *a, b*). The trends in the influence of fuel consumption (thermal capacity of the appliance) on emissions of harmful substances are qualitatively similar to those in the case of household boiler (Fig. 4, *a, b*), namely:

— $[CO]_{3\%\ O}$ *emissions decrease as the fuel flow rate (consumption) grows,* while the concentration of nitrogen oxides $[NO_x]$ increases. In accordance with the calculated thermodynamic prediction, the concentration of [CO] decreases as

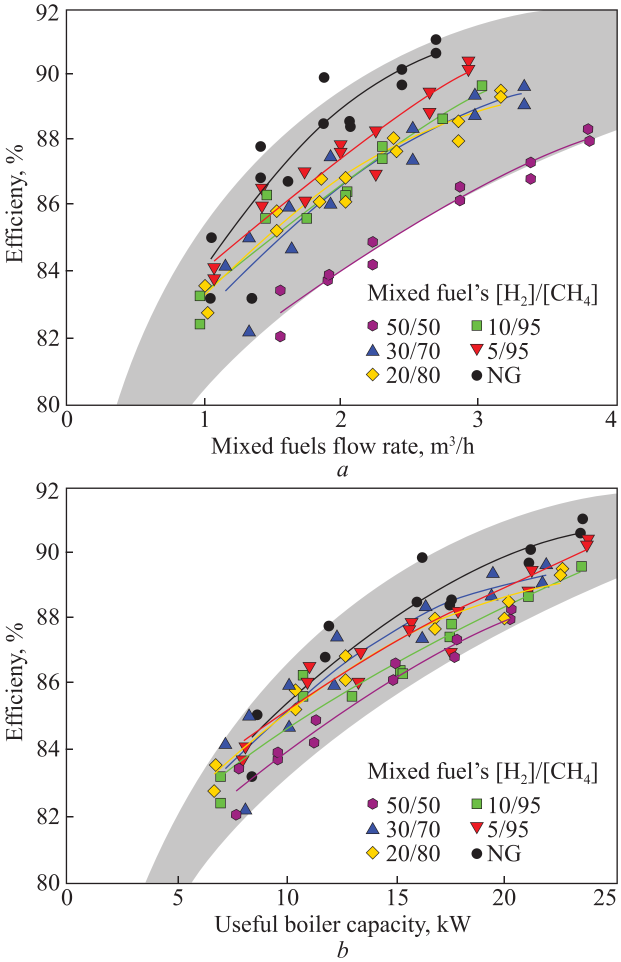

Fig. 3. Dependence of efficiency (%) of *RÖDA* household double–circuit boiler on the fuel flow rate (consumption), m³/h (*a*) and on the heat output of the boiler, kW (*b*). The heat output corresponds to the useful heat absorption of water coolant. $[H_2]/[CH_4]$ ratios in the mixed fuel are shown in the chart within the graph

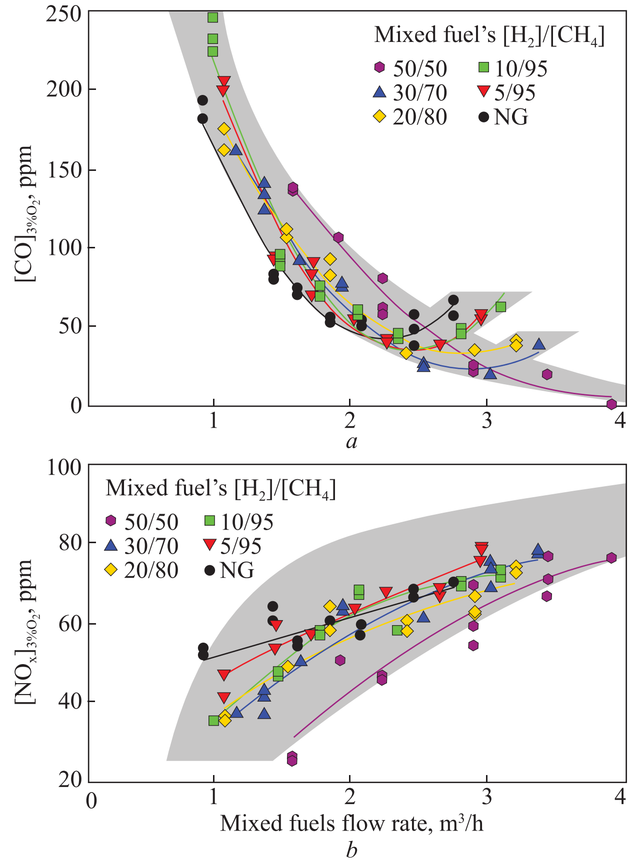

Fig. 4. Dependence of the concentration of harmful emissions of *RÖDA* household double-circuit boiler. Dependence of CO, ppm (*a*) and NOx emissions, ppm, (*b*) for the boiler on the fuel flow rate (consumption), m³/h. $[H_2]/[CH_4]$ ratios in the fuel mix are shown within the graph

the share of H_2 in methane-hydrogen mixed fuel increases. As a result, in the range of the middle and maximum fuel consumptions, the emissions of $[CO]_{3\%\ O2}$ become close to zero in the combustion products (flue gases) of mix $[CH_4]$ / $[H_2]$ = 50/50%, while in the case of natural gas combustion [CO], the emissions makes up to 100 ppm under the mentioned conditions;

— *$[NO_x]_{3\%\ O2}$ emissions grow as the fuel flow rate (consumption) increases.* At the same time, there is observed a tendency towards a significant reduction in NO_x emissions within the entire range of thermal capacity (fuel consumption), as the content of H_2 increases, including the case of the maximum $[H_2]$ content in the tested fuel ($[H_2]$ = 50%). For the tested fuel, at maximum $[H_2]$ concentration ($[H_2]$ = 50% (vol.), the $[NO_x]_{3\%O2}$ emissions grow from 5—10 ppm ($\dot{V}_b = \dot{V}_f \approx 1.0$ l/min) to $[NO_x]_{3\%O2} \approx 60$ ppm (by $\dot{V}_b = \dot{V}_f \approx 6.0$ l/min), while for the fuels with a low $[H_2]$ content ($[H_2]$ = = 5—10 %(vol.)), $[NO_x]_{3\%O2}$ effluents make up 140 ppm and more. Meanwhile, in the case of NG combustion, $[NO_x]_{3\%O2}$ emissions grow from 45 ppm to 90—100 ppm as a result of an increase in the burner heat capacity. Reducing $[NO_x]$ emissions in the case of MG combustion correlates with en-

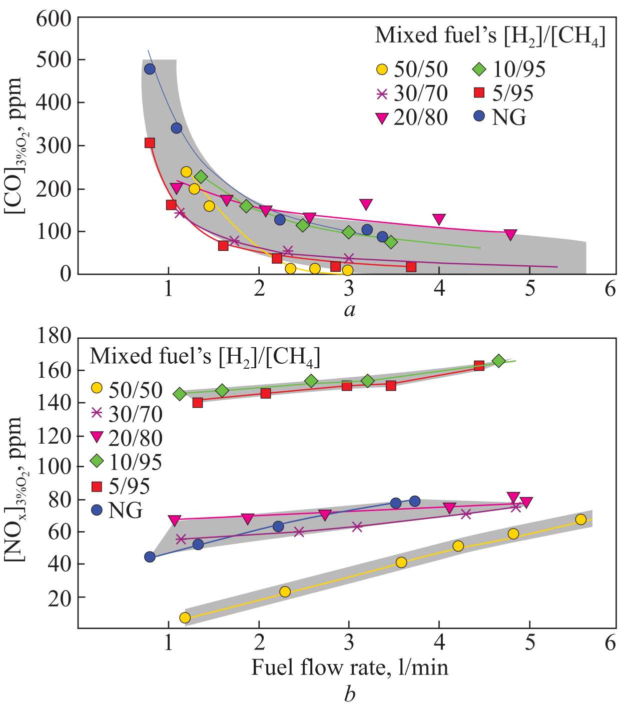

Fig. 5. Dependence of the concentration of harmful emissions of *GRETA* gas cooker on the fuel flow rate (consumption), l /min: *a* — emissions of carbon monoxide CO; [CO], ppm; *b* — emissions of nitrogen oxides NO_x ($NO + NO_2$); $[NO_x]$, ppm. Concentrations of harmful emissions are reduced to concentration $[O_2]$ = 3% in the combustion products. $[H_2]/[CH_4]$ ratios, % vol., in the mixed fuel are shown within the graph

hancing steam formation. The higher the hydrogen content in fuel, the lower the concentration of nitrogen oxides in the exhaust gases 9 combustion products).

Conclusions

1. The current status of the problem of the substitution of natural gas (NG) with mixed gas (MG) containing hydrogen as admixture to NG or the injection of hydrogen into the methane flow in the local gas pipelines has been considered. The European experience of using the MG as fuel for municipal and household gas appliances has been analyzed by the example of pilot projects (UK, Germany) of gas supplying to the settlements located close to gas pipeline distribution networks, for hydrogen concentrations $[H_2]$ = 20—23% (vol.).

2. For the first time in this research, we have discussed the tests of heating boiler and gas cooker stove operating on mixed CH_4—H_2 gas fuel within the range of hydrogen content $[H_2]$ = 0–50% (vol.).

The results of experimental studies of municipal and household appliances operating on MG regarding the power and environmental characteristics of appliances (the efficiency of fuel utilization and emissions of harmful substances: NOx and CO) have been accumulated and generalized.

3. The distinctive feature of household appliances is fuel firing by means of atmospheric burners (AB), the premixed burners operating with Bunsen type flames. In the case of burning MG by means of AB, the composition of MG in terms of the hydrogen share is limited by $[H_2]_{max}$ value (in our case $[H_2]_{max}$ = 50% (vol.)), unlike the industrial combustion systems for which $[H_2]$ content is not limited and may reach 100% (pure hydrogen).

4. Based on the test results, it has been established that the power and environmental characteristics of devices depend on the type and design of gas equipment, operation conditions (the device performance correlates with the fuel gas flow rate and the excess air coefficient), and on the fuel composition, i.e. on the hydrogen content. The range of stable combustion of mixed CH_4—H_2 fuels, as determined for both *GRETA* gas cooker stove and *RÖDA* heating boiler, is sufficiently wide in conditions of practical application. The possibility of reducing the emissions of harmful substances (NO_x and CO) by using MG of tested compositions, in comparison with pure NG, has been confirmed.

Acknowledgments

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ЗАМІЩЕННЯ ПРИРОДНОГО ГАЗУ ВОДНЕМ В УМОВАХ ПОСТАЧАННЯ ПОБУТОВИХ ГАЗОВИХ ПРИЛАДІВ СУМІШЕВИМ ПАЛИВОМ

Вступ. Відповідно до уявлень світового експертного співтовариства, глобальне потепління прикордонного шару в системі «поверхня Землі – атмосферне повітря» пов'язано з наявністю в атмосферному повітрі вуглецевих компонентів (переважно CO_2), а також H_2O, які функціонують як парниковий газ і перерозподіляють радіаційні теплові потоки в оточуючому середовищі.

Проблематика. Основними галузями економіки, що впливають на викиди парникових газів, є промисловість, енергетика та транспорт. З огляду на структуру економіки та паливного балансу України особливе значення має скорочення викидів CO_2 в комунально-побутовому секторі, зокрема, за рахунок використання водню замість органічного палива.

Мета. Визначення можливостей, безпекових умов та перспектив заміщення природного газу воднем шляхом опалювання побутових газових приладів (ПГП) сумішевим газовим паливом (СГП, MG), а також експериментальне вивчення ефективності (ККД) використання СГП (MG) та екологічних характеристик (викиди шкідливих газів: CO, NOx) ПГП.

Матеріали й методи. Проблема декарбонізації навколишнього середовища вирішується заміщенням природного газу (ПГ, NG) метано-водневим сумішевим газом. Вогневі випробування дослідних ПГП: опалювального котла «RODA» (Німеччина) та газової плити «GRETA» (Україна) здійснено з використанням сумішевого газу з вмістом $[H_2]$ до 50 % порівняно зі спалюванням природного газу.

Результати. Експериментально встановлено помірну залежність енергетичних та екологічних характеристик ПГП від вмісту $[H_2]$ в складі палива при варіюванні частки водню в діапазоні $[H_2]$ = 0–50 %.

Висновки. Вперше експериментально доведено прогнозовану теоретично можливість безпечної експлуатації ПГП при спалюванні метано-водневих сумішей із вмістом $[H_2]$ до 50 %. ККД використання палива від його витрат для опалювального котла збільшується із зростанням теплової потужності на відміну від екстремальної залежності ККД газової плити від її теплової потужності.

Ключові слова: атмосферний пальник, взаємозаміщення паливних газів, водень як альтернативне паливо, газова плита, екологічні характеристики димових газів, ефективність використання палива, ламінарна швидкість горіння, опалювальний котел.