Revista Română de Inginerie Civilă, Volumul 14 (2023), Numărul 2

Flow variation and fuel savings when using Hydrogen-Methane mixture as combustible in wall-mounted boilers' operation

Variația debitului și economiile de combustibil la utilizarea amestecului de hidrogen-metan ca combustibil în funcționarea cazanelor montate pe perete

Răzvan CALOTĂ[1], Paul-Dan STĂNESCU[2]

[1,2]Department of Thermodynamic Sciences, Faculty of Building Services, Technical University of Civil Engineering Bucharest,
66 Pache Protopopescu Blvd., 020396 Bucharest, Romania;
E-mail: razvan.calota@yahoo.com; pauldan.stanescu@yahoo.com

DOI: 10.37789/rjce.2023.14.2.1

Abstract: *The article presents a theoretical and experimental analysis that highlights how the employment of a hydrogen- methane mixture influences the variation of the fuel flow for wall-mounted boilers and also aims to evaluate whether fuel economy may be achieved. For a 28 kW condensing boiler, at 50/30 °C water outlet/inlet operating regime and for 2800 h functioning, 431 m^3 of methane gas were saved when using a 23% hydrogen-methane combustible. Correspondingly, at 80/60 °C working regime 599.3 m^3 of methane economy was achieved. The theoretical increasing of the combustible flow of 23,2% is validated by the value obtained experimentally of 22.84% respectively, when the mixture is utilized.*

Keywords: hydrogen combustible; fuel savings

1. Introduction

In order to meet the decarbonization goals established by the European Union for 2050, hydrogen has been identified as a crucial component [1]. Hydrogen has the potential to drastically lower greenhouse gas emissions in a variety of sectors because it is a clean and renewable energy source. Hydrogen fuel cells can be used to power cars in the transportation industry, eliminating the need for gasoline and diesel. This has the potential to significantly reduce transportation-related emissions, which account for a sizable portion of global carbon emissions.

Hydrogen has other use in the industrial sector. When employed as a feedstock in industrial operations, hydrogen can take the place of fossil fuels and greatly reduce emissions. The EU has set an aim of producing at least 40 GW of hydrogen by 2030 and at least 240 GW by 2050 in order to meet these objectives [2]. This will require substantial investments in hydrogen generation, storage, and distribution. The EU has established a "hydrogen alliance" and also a "hydrogen strategy for a climate-neutral Europe" to unite significant players in the hydrogen industry and cooperate toward shared objectives [3]. Hydrogen can be used in the energy sector in addition to wind and solar energy to build a more steady and dependable power system. Hydrogen can be utilized as a backup energy source at times when the wind and sun aren't producing as much energy.

The price of manufacture is one obstacle to using hydrogen as a combustible. The majority of hydrogen is currently produced using fossil fuels, which has a significant impact on greenhouse gas emissions. The cost of production is anticipated to go down as renewable hydrogen generation techniques progress. The infrastructure required to support the use of hydrogen presents another difficulty. This covers hydrogen production, distribution, and storage as well as the tools and vehicles required to use it. The EU is attempting to overcome these obstacles by funding research and development into technologies for producing and storing hydrogen as well as by encouraging the creation of hydrogen infrastructure. Overall, hydrogen has a big chance to help us reach our 2050 decarbonization goals. One of the actions that can be taken in order to reduce hydrocarbons in the combustibles is by replacing them with hydrogen in the wall-mounted boilers that are a key component of the household heating. This is done while simultaneously taking into account the necessity of reducing CO2 emissions, especially from the household heating and hot water producing facilities.

The authors have consistently tested and experimented on combustion equipment powered by gaseous, liquid, or solid fuel within the Centre of the Department of Thermal Sciences part of the Technical University of Civil Engineering Bucharest, Romania, in order to evaluate the combustion efficiency. The fact that the experimental setup has received accreditation from the Romanian National Accreditation Body (RENAR) instills trust in the accuracy of the test results [4]. Many researchers have been interested in the concept the essay addresses up until this point. The investigations that have been done thus far are largely theoretical, and the experimental component is necessary to validate the findings. Articles like [5-15] are valuable in the field, but they generally present numerical modeling or process simulations in specialized software, and in the situation where the data are obtained after conducting experiments, the effects of using the methane-hydrogen mixture on the operation of wall-mounted condensing boilers are not highlighted. Among the most challenging studies involved testing a variety of combustion devices to see how a hydrogen-natural gas mixture affected performance and emissions. This experiment was carried out by Shaffert J. et al. [8]. One of the project's primary findings was that, at 30 vol.% hydrogen admixture, a thermal power reduction of up to 12% compared to the operation with natural gas was observed.

To date, the authors have conducted several studies on the impact of hydrogen-methane mixture, when 10, 20 and 23% of hydrogen is used in the mixture. The article "*CO_2 emissions reduction through increasing H_2 participation in gaseous combustible– Condensing boilers functional response*" published in *Applied Sciences* in 2022 concluded that an increase in combustible flow with 16% is needed in order to maintain the boiler thermal power and to overcome the fact that hydrogen has lower net and gross calorific values when compared to methane. The paper "*The direct effect of enriching the gaseous combustible with 23% Hydrogen in condensing boilers' operation*" published in Energies in 2022 emphasizes the reduction of carbon dioxide emissions in the atmosphere when using hydrogen in percentage of 23% in the mixture. The annual reduction in CO2 emissions for a 28 kW condensing boiler averages 1.22 t; this number was obtained experimentally and agrees with the theoretical assessment.

In addition to the conclusions obtained from previous studies this article investigates the flow variation and fuel savings when using Hydrogen- Methane mixture as combustible in wall-mounted boilers' operation. Considering the fact that the combustible flow increases it is mandatory to assess the net methane savings that can be achieved. Secondly, the research examines the differences between the combustion of pure methane and the combustion of a methane-hydrogen mixture from a thermodynamics perspective.

2. Materials and Methods

The installation of a 28 kW condensing boiler with flattened pipes in a specific circuit for testing wall-mounted boilers, in particular, was part of the experimental research described in this article. The stand has several different kinds of sensors for measuring the flow of gaseous combustibles, the temperature of the water, and water flow. Table 1 shows the kind of sensor, measurement cycle, and accuracy. To ensure proper operation and the accuracy of the data shown, all sensors are calibrated every two years.

All test results are confidently supported by the experimental circuit's Renar accreditation, which additionally ensures credibility.

The Experimental Stand is presented in Figure 1 and its design meets the requirements of the European testing standards [16,17].

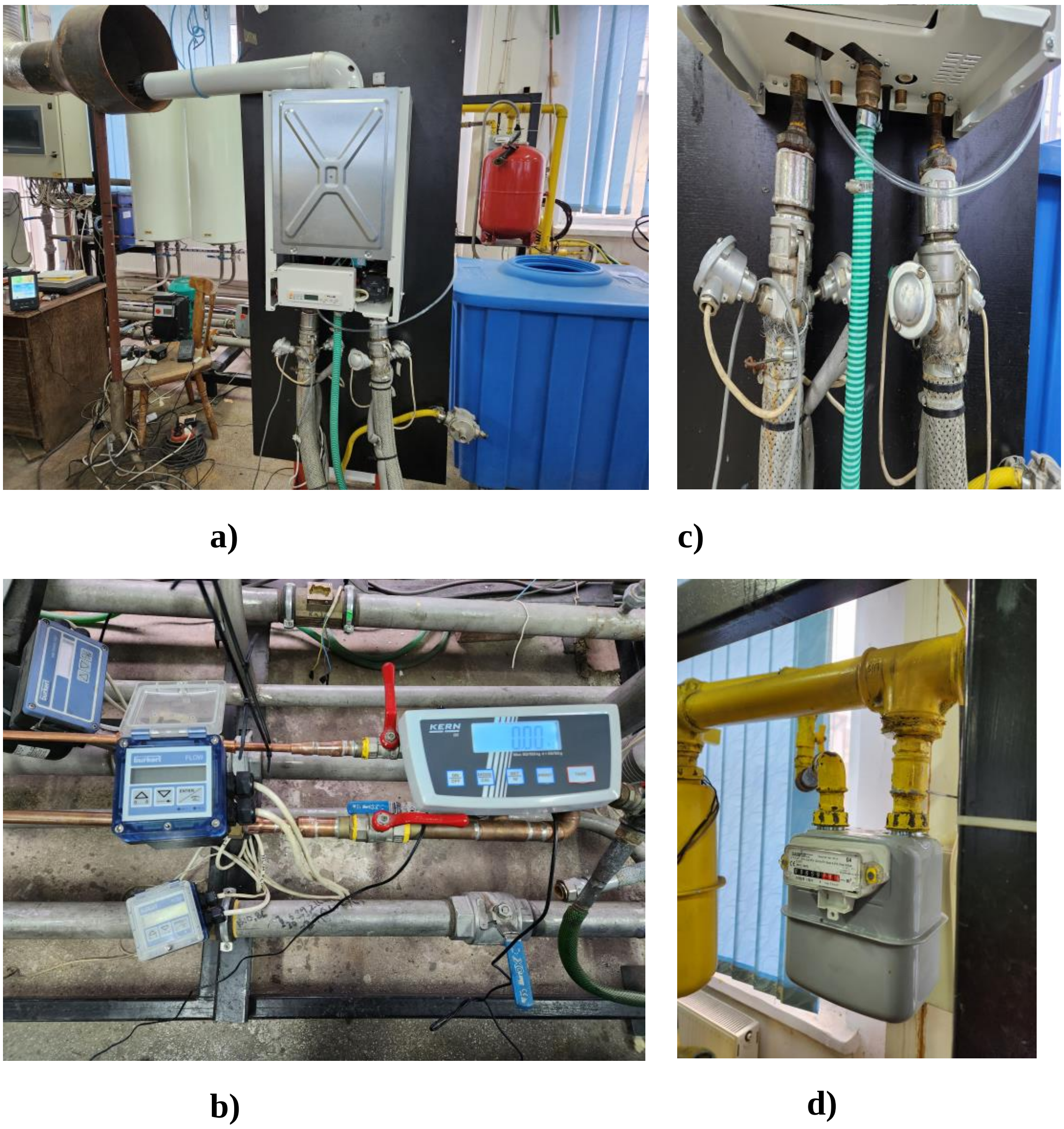

Figure 1. a) Experimental stand **b)** Water flow meters **c)** Temperature sensors **d)** Gas meter (Source: own elaboration)

Table 1.

Measurement sensors (used in this research)

Sensor/ Device	**Measurement**	**Measurement range**	**Accuracy**
Thermal resistance	Temperature T[°C]	-20 to 100 °C	±0,1%
Propeller flow meters	Water velocity [m/s]	0.2 to 10 m/s	±0,5%
Gas meter	Gas flow [m^3/h]	0.6 to 6 m^3/h	±0,5%

Through a theoretical analysis of the combustion process, important parameters necessary for adjusting the experimental stand are determined, such as the theoretical volume of air required for combustion, the theoretical volume of combustion gases and the maximum percentage of CO2 depending on the type of fuel, which consist an input data for flue gas analyzer setting.

The stoichiometric thermodynamic calculation assumes that combustion takes place without excess air and the chemical reactions are complete. Thermodynamics deals in particular with the phenomena of controlled combustion within thermal equipment and through calculation different parameters can be obtained:

- Determining the volume of air required to burn a fuel with a known chemical composition
- Determination of the excess air required for complete combustion
- Determination of the volume of combustion gases resulting from the combustion process

When combustion results in compounds such as CO, NO, SO, CH4, it means that the reaction with oxygen of the fuel elements was not complete, or in other words, enough oxygen was not delivered for combustion, resulting in incomplete combustion.

We consider the gaseous fuel unit (one cubic meter) composed of the volume shares "co" of carbon monoxide, "h" of hydrogen, "$c_m h_n$" of hydrocarbon (each separately), "$h_2 s$ " of hydrogen sulfide, "o" of oxygen, " co_2" of carbon dioxide and "n'" of nitrogen.

Following the analysis of the combustion reaction with oxygen of the combustible components in the gas mixture we can obtain the minimum air volume for gaseous combustible stoichiometric burning (Eq.1), flue gas minimum volume (Eq.2) [18,19].

$$\begin{aligned} \mathrm{V_{air,min.}} = {} & 2{,}38 \cdot (\mathrm{co} + \mathrm{h}) + 7{,}143 \cdot \mathrm{h_2 s} + 4{,}762 \cdot \sum \left(\mathrm{m} + \frac{\mathrm{n}}{4}\right) \cdot \mathrm{c_m h_n} \\ & - 4{,}762 \cdot \mathrm{o} \left[\frac{\mathrm{m^3 air}}{\mathrm{m^3\ comb.}}\right] \end{aligned} \tag{1}$$

$$\begin{aligned} \mathrm{V_{g,min.}} = {} & \mathrm{V_{CO_2}} + \mathrm{V_{H_2O}} + \mathrm{V_{SO_2}} + \mathrm{V_{H_2S}} + \mathrm{V_{N_2}} \\ = {} & 0.01 \cdot \left(\mathrm{co} + \mathrm{co_2} + \sum \mathrm{m} \cdot \mathrm{c_m h_n}\right) + 0.01 \cdot \left(\mathrm{h} + \mathrm{h_2 s} + \sum \frac{\mathrm{n}}{2} \cdot \mathrm{c_m h_n}\right) \\ & + 0.01 \cdot \mathrm{h_2 s} + \left(0.01 \cdot \mathrm{n'} + 0{,}79 \cdot \mathrm{V_{aer,min.}}\right) \left[\frac{\mathrm{m^3\ gases}}{\mathrm{m^3\ comb}}\right] \end{aligned} \tag{2}$$

$$V_g = V_{g.min.} + (\lambda - 1) \cdot V_{air,min.} \left[\frac{m^3\ gases}{m^3\ comb.}\right] \quad (3)$$

The theoretical evaluation involves the consideration of initial values for certain quantities such as excess air, λ and operating efficiency, η. All these values will be estimated based on the experience of testing similar equipment. The excess air can be considered to be 1.3, which consists of an average value for this parameter obtained by the authors during noticeably testing activities. By inserting the excess air into Eq.(3) the total volume of flue gases is obtained.

In order to carry out the study, we used the technical sheets of the gas cylinders used in the experimental part. Two type of gases were used, namely G20 which is essentially methane and G222, a mixture between methane and 23% hydrogen. This specific composition is clearly described in the test standards [20].

The volumetric composition was taken from these sheets.

The percentage volume shares of the components in the mixture are presented in Table 2. The components present as residues in the G20 mixture (isobutane, hydrogen, carbon monoxide, isopentane, etc.) constituted a maximum percentage of 0.1% and were neglected.

Table 2.

Gaseous combustible composition

Combustible type	Volumetric composition
G222	h 23% ; $c_mh_n \Rightarrow ch_4$ 77%
G20	$c_mh_n \Rightarrow ch_4$ 95,6% c_2h_6 3,24% ; c_3h_8 0,54%; c_4h_{10} 0,08%; co_2 0,44%

Another important parameter regarding the gaseous fuel is the net heat of combustion (lower calorific value). This quantity was also extracted from the data sheets of the two substances, at the reference temperature of 0°C. G222 has a value of $29{,}930\ kJ/m^3$ and G20 a value of $36{,}879\ kJ/m^3$ respectively. From the start it can be seen that the mixture of 23% hydrogen with methane produces a lower amount of heat when compared to pure methane.

Combustible flow is related to the lower calorific value, boiler thermal power and its efficiency as in Eq (3).

$$B = \frac{\dot{Q}}{\eta \cdot H_i} \left[\frac{m^3\ comb.}{s}\right] \quad (4)$$

The tested equipment is a wall-mounted condensing boiler, flattened pipe type with a declared nominal heat load of 28 kW.

To be able to theoretically obtain the combustible flow required for operation, for each gaseous fuel, the efficiency was considered 97%, an averaged value for similar equipment based on the testing team's experience.

3. Results

This section contains theoretical and experimental results regarding the combustible flow variation when converting from methane gas (G20) to a 23% hydrogen- methane mixture (G222).

From theoretically point of view the volume of fuel consumed is determined by applying Eq. (4). The results are presented in Table 3.

Table 3.

Gaseous combustible flow (theoretical)

Combustible flow	G222	G20
$B_{comb.}\left[\frac{m^3 comb.}{h}\right]$	3,472	2,818

Theoretically, the combustible flow should increase with 23,2% when converting to G222 from G20 gas.

By using Eq. (1) and (3), air and total flue gases volume can be determined. The results are plotted in Table 4.

Table 4.

Air and flue gases volume (thermodynamic analysis)

Parameter	G222	G20
$V_{air,min.}\left[\frac{m^3 air}{m^3\ comb.}\right]$	7.88	9.798
$V_{air}\left[\frac{m^3 air}{m^3\ comb.}\right]$	10.244	12.737
$V_{g.min.}\left[\frac{m^3 gases}{m^3\ comb.}\right]$	8.891	10.976
$V_{g}\left[\frac{m^3 gases}{m^3\ comb.}\right]$	11.255	13.915

In addition to the theoretical results, the outcome of the experimental study are also presented.

A complete test procedure for a wall-mounted boiler, in addition to safety tests, verification of the proper operation of the measurement sensors, determination of the consumed electrical energy, must contain experimental data sets recorded in stationary working regime, for the following situations:

- Nominal, average, reduced thermal load (30% of nominal load) for the working regime represented by the outlet/inlet temperature of the heating agent 80/60 °C
- Nominal, medium and reduced thermal load for the 50/30 °C condensing operating mode
- For NOx emissions, tests are carried out at partial thermal loads of 20%, 40%, 60% and 70% of the nominal thermal load and then the values are averaged according to the formula in the standard for determining the class of NOx emissions.

According to the testing Standards [18,19], the experimental research can only be conducted under circumstances where the monitored parameters do not vary for a period of 10 minutes by more than 0,5 °C for working agent temperatures and by more than 0,5% for flow. For this study the testing was conducted only at nominal thermal load of 28 kW for 50/30 °C and 80/60 °C operating regimes.

Only significant parameters for this study were extracted from the experimental data and are presented in Table 5. The values are averaged for a 10 minute testing time interval.

Table 5.

Experimental values

Combusti	Water	Gas flow	Water [°C]	Water [°C]	Excess air	Operating
G222	1194	3.383	49.78	30.3	1.33	50/30 °C
G20	1246	2.754	50.04	29.7	1.31	
G222	1108	3.307	80.04	60.33	1.33	80/60 °C
G20	1130	2.764	80.18	60.3	1.31	

4. Discussion

In the the authors' previous research, emphasis was placed especially on the reduction of carbon dioxide emissions when hydrogen is used in a mixture with methane gas.

Turning the attention only to the combustible flow consumed per hour and taking into account the fact that the G222 mixture contains 23% hydrogen the following aspects should be emphasized:

For the 50/30 °C operating regime, the condensing operating regime, the average G20 flow rate is 2.754 m3/h and the G222 flow rate is 3.383 m3/h. Thus, in percentage terms, an experimental increase in flow rate by 22.84% is found. Considering the G222 mixture, the percentage of methane is 77%, thus the flow consumed in operation, only referring to methane gas, is 2.6 m^3/h. Therefore, a total saving of methane gas obtained when switching from G20 to G222 fuel of 0.154 m^3/h. If we relate this value to an average operating time of 2800 hours per year, we obtain an economy of 431 m^3 of methane gas, which in the future context of overcharging per cubic meter of gas is significant. This value only concerns one plant, but when it is extrapolated to the total number of wall-mounted boilers that could be fed with G222 mixture, the effect can be significant.

For the 80/60 °C working regime, the average flow rate of G20 is 2.764 m^3/h and the flow rate of G222 is 3.307 m^3/h. Thus, an experimental increase in flow rate by 19.64% is found. For the G222 mixture, the flow consumed in operation, concerning only the methane gas, is 2.55 m^3/h. The saving of methane gas obtained when switching from G20 to G222 fuel is 0.214 m^3/h. For an yearly operating time of 2800 hours, 599.3 m^3 economy of methane gas is achieved.The results obtained for both operating regimes are similar since the fuel flow doesn't have an important variation. However, the results related to the condensing mode of operation 50/30 °C, where the efficiency is the highest are more important and will be further considered as reference.

In view of air and total gas volumes, by analyzing Table 4, an increase of both values can be noticed, when using G222 in comparation with G20. Thus, the total air volume is 19.57% lower and the total flue gases volume is 19,11% lower relative to a cubic meter of combustible. However, this values can be misleading if the fact that the flow is higher when dealing with G222 (Table 3) due to its lower calorific value. In line with this aspect, the air flow and flue gases flow are determined and presented in Table 6.

Table 6.

Air and flue gases flow (thermodynamic analysis)

Parameter	G222	G20
$\dot{V}_{air}\left[\frac{m^3 air}{h}\right]$	35.57	35.89
$\dot{V}_{g}\left[\frac{m^3 gases}{h}\right]$	39.08	39.21

Furthermore, from the experimental data plotted in Table 5, the excess air is slightly higher when the boiler is fed with G222, so in both cases the air volume and the flue gases volume are roughly similar.

When comparing the experimental data with the theoretical ones, it can be seen that the initially assumed value for the excess air is confirmed and also the difference between the fuel flow values in the two analyzed cases is validated. The theoretical value of 23,2% is validated by the value obtained experimentally of 22.84% respectively.

5. Conclusions

When methane is released into the atmosphere, it acts as a potent greenhouse gas and accelerates climate change. The only result of hydrogen combustion, on the other hand, is water vapor, making it a cleaner and greener alternative. Additionally, some industrial processes can be made more cost-effective and efficient by employing hydrogen as a fuel source in boilers. It is important, however, that in the case of the hydrogen implementation of as a fuel, there should be deductions at the level of European Union like in the case of Germany. This research focuses on the combustible flow variation, when converting from G20 (methane gas) to G222 (23% hydrogen and 77% methane) in wall-mounted boilers' operation. A roughly 23% flow increase was discovered both theoretically and experimentally. With regard to methane savings, in condensing operating regime, only one plant can achieve 431 cubic meters savings yearly. The authors will continue the experimental research with fuel mixtures containing higher percentages of hydrogen to investigate both the behavior from the point of view of the energy efficiency, greenhouse gas emissions and the safety in operation at the burner level.

References

1. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en (accessed on 15 December 2022).

2. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en (accessed on 15 December 2022).

3. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301 (accessed on 19 December 2022).

4. https://www.renar.ro/index.php/oec/get_oec_details/41741 (accessed on 20 December 2022).

5. Yue Xin, Ke Wang, Yindi Zhang, Fanjin Zeng, Xiang He, Shadrack Adjei Takyi and Paitoon Tontiwachwuthikul Numerical Simulation of Combustion of Natural Gas Mixed with Hydrogen in Gas Boilers, Energies 2021, 14, 6883; https://doi.org/10.3390/en14216883

6. Jörg Leicher, Johannes Schaffert, Hristina Cigarida, Eren Tali, Frank Burmeister, Anne Giese, Rolf Albus, Klaus Görner, Stéphane Carpentier, Patrick Milin and Jean Schweitzer- The Impact of Hydrogen Admixture into Natural Gas on Residential and Commercial Gas Appliances, Energies **2022**, 15, 777. https://doi.org/10.3390/en15030777

7. Paul Glanville, Alex Fridlyand, Brian Sutherland, Miroslaw Liszka, Yan Zhao, Luke Bingham and Kris Jorgensen- Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance, Energies 2022, 15, 1706. https://doi.org/ 10.3390/en15051706

8. Schaffert, J.; Fischer, P.; Leicher, J.; Burmeister, F.; Flayyih, M.; Cigarida, H.; Albus, R.; Görner, K.; Mili, P.; Carpentier, S.; et al. Impact of Hydrogen Admixture on Combustion Processes—Part II: Practice. Deliverable D2.3 as Submitted from the THyGA Project. 2020. Available online: https://thyga-project.eu/wp-content/uploads/20201211-D2.3-Impact-of-Hydrogen-in-Practice_final.pdf (accessed on 03 March 2022).

9. Suchovsky, C.J., Ericksen, L., Williams, T.A., Nikolic, D.J. (2021). Appliance and Equipment Performance with Hydrogen-Enriched Natural Gases. Canadian Standards Association, Toronto, ON.

10. Harmen de Vriesa,, Howard B. Levinskyb- Flashback, burning velocities and hydrogen admixture: Domestic applianceapproval, gas regulation and appliance development, Applied Energy 259 (2020) 114116, https://doi.org/10.1016/j.apenergy.2019.114116

11. M.S.Boulahlib, F.Medaerts, M.A.Boukhalfac, Experimental study of a domestic boiler using hydrogen methane blend and fuel-rich staged combustion, International Journal of Hydrogen Energy, Volume 46, Issue 75, 29 October 2021, Pages 37628-37640, https://doi.org/10.1016/j.ijhydene.2021.01.103

12. Gianluigi Lo Basso, Benedetto Nastasi, Davide Astiaso, Garcia Fabrizio Cumo, How to handle the Hydrogen enriched Natural Gas blends I combustion efficiency measurement procedure of conventional and condensing boilers, Energy 123 (2017) 615e636, http://dx.doi.org/10.1016/j.energy.2017.02.042

13. Ruggero Amaduzzi, Marco Ferrarotti and Alessandro Parente- Strategies for Hydrogen-Enriched Methane Flameless Combustion in a Quasi-Industrial Furnace, 2021, Frontiers in Energy Research, doi: 10.3389/fenrg.2020.590300

14. Francesco Scrignoli , Filippo Vecchio, Francesco Legrottaglie, Enrico Mattarelli and Carlo Alberto Rinaldini- Numerical Investigation of Dual Fuel Combustion on a Compression Ignition Engine Fueled with Hydrogen/Natural Gas Blends, Fuels 2022, 3, 132–151. https://doi.org/10.3390/fuels3010009

15. John G. Ingersoll- The Renewable Hydrogen–Methane (RHYME) Transportation Fuel: A Practical First Step in the Realization of the Hydrogen Economy, Hydrogen 2022, 3, 84–112. https://doi.org/ 10.3390/hydrogen3010008

16. EN 15502-2-1:2012+A1:2016, Gas-fired central heating boilers Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1 000 kW, https://magazin.asro.ro/ro/standard/252192 (accessed on 20 December 2022).

17. EN 15502-1:2021, Gas-fired heating boilers - Part 1: General requirements and tests, https://magazin.asro.ro/ro/standard/277890 (accessed on 20 December 2022).

18. Razvan Calota "Bazele termodinamicii tehnice pentru pompieri", MATRIX rom Publishing House, 2019, ISBN 978-606-25-0519-6.

19. Antonescu N. Burning installations and boilers with high energetical efficiency and low pollution emissions -2018, 274 pgs. MatrixRom Bucharest – ISBN 978-973-755-699-8

20. EN 437:2021 Test gases. Test pressures. Appliance categories. https://magazin.asro.ro/ro/standard/276144 (accessed on 11 October 2022)