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The Direct Effect of Enriching the Gaseous Combustible with 23% Hydrogen in Condensing Boilers' Operation

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Abstract: Following the international trend of using hydrogen as combustible in many industry branches, this paper investigates the impact of mixing methane gas with 23% hydrogen (G222) on condensing boilers' operation. After modeling and testing several boilers with heat exchange surface different designs, the authors gathered enough information to introduce a new concept, namely High-Performance Condensing Boiler (HPCB). All the boilers that fit into this approach have the same operational parameters at nominal heat load, including the CO_2 concentrations in flue gases. After testing a flattened pipes condensing boiler, a CO_2 emission reduction coefficient of 1.1 was determined when converting from methane gas to G222 as combustible. Thus, by inserting into the national grid a G222 mixture, an important reduction in greenhouse gases can be achieved. For a 28 kW condensing boiler, the annual reduction in CO_2 emissions averages 1.26 tons, value which was experimentally obtained and is consistent with the theoretical evaluation.

Keywords: CO_2 emissions; hydrogen (H_2) combustible; energy efficiency; decarbonization

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1. Introduction

In line with the challenging context today, due to global warming as well as the conflicts taking place all over the world, at the level of the European Union, alternative energy production solutions must be promptly found to mitigate the danger of long Blackout periods. One of the alternatives that are becoming more and more widespread, is the use of ecologically produced hydrogen to fuel the combustion processes that take place in the gas turbines of large power plants. The European Commission approved up to 5.2 billion euros in public funding for research involving "low-carbon hydrogen" production, transport, and storage, starting in October 2022 [1].

Thus, researchers are currently in a permanent search for the most ecological and simple ways to obtain hydrogen so that it can be used later as combustible. At the same time, it is mandatory to eliminate the main problem regarding the use of hydrogen as a fuel, namely, the large amount of energy consumed for its production through the means of classical methods. A very recent study, conducted by Amberchan G et al. [2] in 2022, found a simple method for producing hydrogen from water at room temperature by using Ga nanoparticles.

Of great interest is also the production of hydrogen with the use of photovoltaic panels. Karayel K. et al. [3] recently investigated Turkey's green hydrogen production potential using solar photovoltaic cells. The energy generated is directed to electrolysis equipment. Berrada A. et al. [4] carried out a study regarding the technical and economical assessment of hydrogen production from solar energy. The study highlighted the potential for CO_2 emissions reduction using hydrogen as combustible. Zhang J. et al. [5] have done an exhaustive life cycle assessment for three methods of hydrogen production by using solar energy. Like the previous study, the environmental impact had been investigated.

Following the trend briefly presented above, Oradea, which is one of the most developed cities in Romania, will implement, starting at the end of 2022, a project in which the gas turbine inside the power plant will use hydrogen produced by means of a photovoltaic panels park. Succeeding the introduction of hydrogen alongside natural gas in the fuel mixture that powers the turbine, in a percentage of 15% of the mixture, the greenhouse emissions in the environment will be reduced by up to 5% [6].

Oberg S. et al. [7] recently studied the opportunity to introduce hydrogen-fueled gas turbines in future large energy systems. The results showed that in order to comply with the regulation regarding carbon emissions reduction to minimum values until 2050, hydrogen-powered gas turbines could have a significant contribution. Reale F. et al. [8] investigated the combustion efficiency and the greenhouse gas emission for a small gas turbine fueled with methane-hydrogen mixtures containing up to 10% of hydrogen and emphasized the advantages and disadvantages of enriching the gaseous fuel mixture with hydrogen. In the same scope, Lu J. et al. [9] evaluated the combustion characteristics of a micro gas turbine fueled by a methane-hydrogen mixture, referring in particular to the manner in which the air supply is made and the combined effect on atmospheric emissions. Going to a smaller scale regarding the combustion process of mixtures between natural gas and hydrogen, their applicability in small wall-mounted or in larger boilers must be stressed, these being one of the most used equipment for heating individual homes at the level of the European Union and, in particular, in Romania.

This aforementioned object is of particular importance as it leads not only to the reduction of carbon dioxide emissions but also to the reduction of dependence on natural gas by reducing the volume occupied by methane gas in the fuel mixture. Boulahlib M. et al. [10] evaluated the performance of a domestic boiler using a hydrogen methane blend. However, the analysis carried out by the authors concerned a classic type of boiler, without condensation. The authors concluded that a moderate hydrogen blend rate of 20% is recommended for achieving an optimal operation.

Lo Basso et al. [11] suggested a combustion efficiency measurement procedure for conventional and condensing boilers using hydrogen-enriched natural gas blends. This very comprehensive study is limited to only using the Ostwald diagram and UNI 10389 Standard, without referring to experimental results and evaluations.

Likewise, Xin Y. et al. [12] theoretically analyzed the combustion of natural gas mixed with hydrogen in gas boilers. The study aimed at a swirl-type burner used in boilers without condensation, and as the main outcome, the gas emission decreased together with the CO_2 and N_2 concentration in flue gases. Schiro F. et al. [13] theoretically evaluated the impact of hydrogen-enriched natural gas on domestic gas boilers. Some recommendations based on analytical conclusions have been done, such as the need to assure a special burner design for high hydrogen enrichment percentage, considering the increased tendency to unwanted ignition and flashing back. This deduction comes from the fact that the 23% hydrogen methane gas mixture (generically called G222) is used in boiler testing in view of the application of the CE marking which is like a flashback limit gas [14,15].

Glanville P. et al. [16] evaluated the impact of hydrogen/natural gas blends on partially premixed combustion equipment. With a hydrogen percentage of up to 30% in the mixture, during experiments, the flashback did not occur. This conclusion is important, but it should be considered that the burners tested are atmospheric type and are not suitable for condensing boilers.

A more targeted study on condensing boilers was conducted by Lamioni R. et al. in 2022 [17]. In the study, numerical simulations of combustion and pollutant emissions related to condensing boilers with specific types of burners. The authors concluded that one of the major drawbacks that come together with the use of hydrogen in the gaseous combustible mixture is the high adiabatic flame temperature that triggers the NO thermal formation, as opposed to operating only with methane gas (GN). As the authors also specified in their conclusions, all these numerically modeled results are valuable, but they must be complemented by experimental tests to validate them.

In Romania, a pilot project will take place between November 2022 and October 2024, and aims to analyze and demonstrate that, from a technical point of view, it is possible and safe to add hydrogen, in a proportion of 20% by volume, to the distribution networks and facilities of existing natural gas grids in Medias, Romania [18]. The purpose of the project is both to analyze the compatibility and behavior of the distribution networks' elements and to evaluate the possibility of their conversion to the GN-H2 mixture. Consumer installations (pipes, appliances) and the components of the distribution system (pipes, connections, fittings, fittings, regulators, gas flow meters) will not be modified for this process.

After carefully studying the relevant bibliography in the field, the authors concluded that experimental research on the operation of condensing boilers fed with hydrogen and methane gas mixture is extremely necessary to improve knowledge in the field. The first step in this direction was made by the authors through the article [19], in which, both theoretical and experimental evaluations have been conducted on two types of condensing boilers: a corrugated boiler and a finned-pipe one. The study's conclusion is that an increase in the combustible flow by 16% is necessary at a 20% H_2 concentration in the mixture, to keep constant the boiler's thermal efficiency. The boilers' CO_2 emissions decreased by about 7%.

As a complement to the aforementioned study, the authors continued the theoretical and experimental research by evaluating in the present work a condensing boiler with flattened pipes. Nowadays, this type of boiler is one of the most sold on the boilers' market and thus its experimental evaluation was essential. The hydrogen concentration in the mixture was increased to 23% to match the Standard G222 gas mixture, flashback gas, according to legislation. The experimental tests were conducted within the Centre of the Department of Thermal Sciences, part of the Technical University of Civil Engineering Bucharest, on an experimental stand accredited by the Romanian National Accreditation Body (RENAR) [20]. The EA Multilateral Agreement (EA MLA) is a signed agreement between the EA members whereby the signatories recognize and accept the equivalence of the accreditation systems operated by the signing members, and RENAR is a signatory part. Taking into account these aspects, all the experimental results presented in this article can be considered reliable.

The aim of the study is to highlight the main differences in operation when the boiler is fed with methane (G20) and alternatively with a 23% hydrogen-methane mixture (G222). While maintaining a constant thermal load, the variation of the fuel flow, the excess air, as well as the combustion gas emissions, especially the carbon dioxide emissions, will be evaluated. A second main objective of this work is the validation of the results from the previous article [19] in the case of the flattened pipes boiler. Since the outcomes of the study are in line with previous research, thus covering three of the most important condensing boilers' design, a new concept is introduced under which all small condensing boilers could be included. Thus, the direct effect of enriching the gaseous combustible with 23% hydrogen in condensing boilers' operation could be evaluated by measuring the emissions for an existing boiler fed with G20 combustible gas and by decreasing their respective value with a specific coefficient obtained by the authors in this study.

2. Materials and Methods

The experimental research presented in this article involved the installation of a condensing boiler with flattened pipes in a dedicated circuit for testing wall-mounted boilers, particularly. The stand is equipped with several types of sensors for measuring the water temperature, water, and gaseous combustible flow as well as with regulators to stabilize the gas pressure. The sensors' type, measurement interval, and accuracy are displayed in Table 1. All the sensors are calibrated at a two-year interval including the gas analyzer used for the evaluation of pollutant emissions in the environment, to ensure their correct operation and the reliability of the displayed data.

Table 1. Measurement sensors and devices.

Sensor/Device	Measurement	Measurement Range	Accuracy
RTD (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%
Gas analyzer (Afriso)	Flue gases' concentration (ppm)	0 to 21% vol. O_2 0 to CO_2 max. for CO_2 0 to 1000 ppm CO 0 to 500 ppm NO_x	±0.2% CO_2 and O_2 ±5 ppm CO ±0.1% NO_x

The experimental circuit, laid out in Figure 1, is RENAR-accredited, a fact that gives confidence to all the test results and assures the obtaining of valuable conclusions when comparing the results with the outcome from mathematical modeling.

(**a**) (**c**)

(**b**) (**d**)

Figure 1. (**a**,**b**) Experimental stand; (**c**) Flattened pipes boiler, and (**d**) Gas supply plant.

The boiler with flattened pipes circuit is schematically presented in Figure 2.

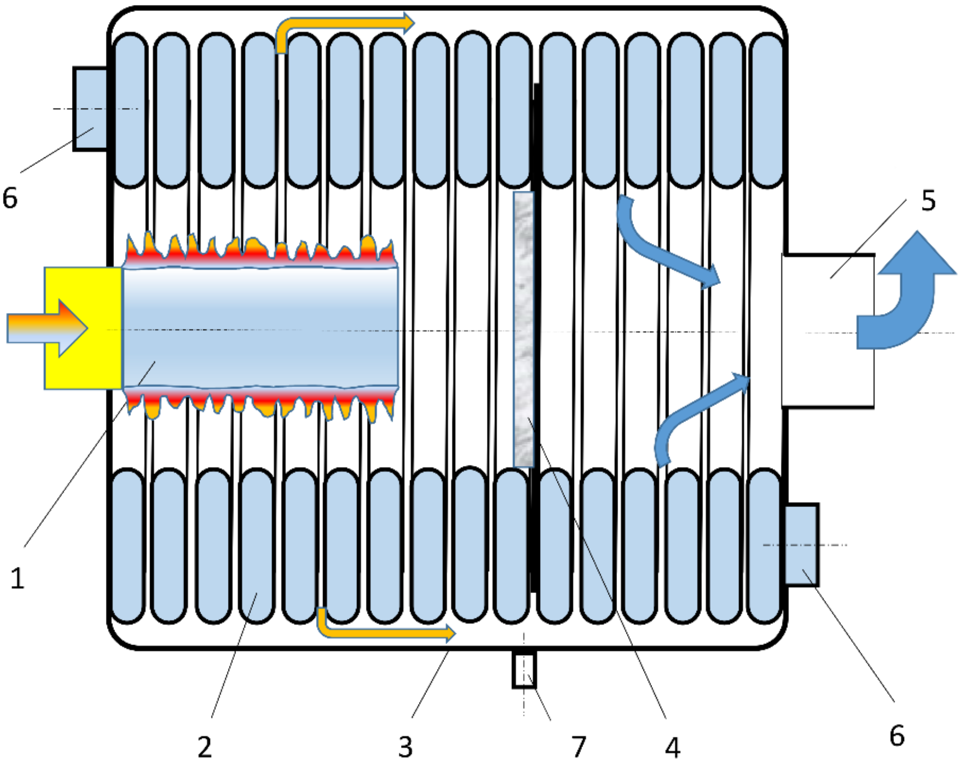


Figure 2. Boiler with flattened pipes.

Water enters and exits the flattened pipes heat exchanger 2, through the inlet/outlet 6 and flows in counter-current with the flue gases in order to provide the means for the condensing process to produce. The air-gaseous combustible mixture is premixed in burner 1 and the resulting flue gases pass through the very narrow section between pipes 3, having a very low characteristic length, and implicitly, a very intense heat transfer coefficient to the pipes' wall. The gases are also directed by means of a partition wall 4 in the second section of the heat exchanger from where they are sent to chimney 5. In the heat exchanger's second part, the condensing process takes place, due to the pipes' wall temperature which is lower than the water vapor from the flue gas dew point. The condensate is eliminated through 7 from the circuit.

The study aims to evaluate the combustion of two gaseous fuels, pure methane gas, code G20, and a gaseous fuel mixture between 23% hydrogen and methane, respectively, code G222. In order to carry out the research, the volume percentage composition was taken from the gas technical sheets and is presented in Table 2.

Table 2. Gaseous combustible composition.

Combustible Type	Volume Percentage Composition
G222	$H_2 = 23\%$ $CH_4 = 77\%$
G20	$CH_4 = 95.6\%$ $C_2H_6 = 3.24\%$ $C_3H_8 = 0.54\%$ $C_4H_{10} = 0.08\%$; $CO_2 = 0.44\%$

Another very important parameter regarding the gaseous fuel is the net heat of combustion (lower calorific value). This quantity was also extracted from the technical sheets, at the reference temperature of 0 °C, and it can be found in Table 3.

Table 3. Net and gross calorific values.

Combustible Type	Net Calorific Value	Gross Calorific Value
G222	$29,930\ kJ/m^3$	$33,480\ kJ/m^3$
G20	$36,879\ kJ/m^3$	$40,970\ kJ/m^3$

3. Results

In order to set the gas analyzer to work properly, the stoichiometric combustion correlations were used in order to determine the maximum theoretical value of carbon dioxide percentage in the dry combustion gases' volume, using the values from Table 2 [21]. It is necessary to use the dry volume of combustion gases obtained by subtracting the volume of water vapor from the total volume. This is because, in the gas analyzer before the measurement of the volumetric participation of each component in the flue gases is carried out, the gases are dehydrated so that the electrochemical cells are not affected by the presence of water. According to the technical sheet, the tested boiler with flattened pipes has a 105.8% efficiency and delivers a 28 kW heat flux for a 50/30 °C condensation regime. The results are provided in Table 4.

Table 4. Calculated values for determining the maximum CO_2 percentage in flue gases (CO_2 max.).

Parameter	G222	G20
$V_{air,min.}\left[\frac{m_N^3 air}{m_N^3\ comb.}\right]$	7.88	9.798
$V_{CO_2,flue\ gases}\left[\frac{m_N^3 CO_2}{m_N^3\ comb.}\right]$	0.77	1.045
$V_{H_2O,flue\ gases}\left[\frac{m_N^3 H_20}{m_N^3\ comb.}\right]$	1.896	2.191
$V_g\left[\frac{m_N^3 flue\ gases}{m_N^3\ comb.}\right]$	8.891	10.976
$V_{g.dry}\left[\frac{m_N^3 flue\ gases}{m_N^3\ comb.}\right]$	6.995	8.785
CO_2 max.[%]	11	11.9

For the 50/30 °C condensation regime, it is assumed that a maximum of 70% of the total water vapor content of the combustion gases condenses during operation. The condensation process is complex and takes place on a certain area of the heat exchange surface, characterized by a wall temperature lower than the dew point temperature.

For the condensation process to be as efficient as possible, the dew point temperature must be as high as possible. The dew point temperature varies directly proportional to the partial pressure of water vapor in the combustion gases, which in turn, when assuming a value of the combustion gas pressure of 1 atm, decreases as the flue gas advances on the heat exchanger depth. Thus, a 100% condensing efficiency is not possible to be attained.

Theoretically, when the phenomenon of condensation occurs and the fuel flow is kept constant, the thermal load increases, as a result of the contribution of the latent heat of condensation given up by the water vapor during the phase change. Thus, considering these input data, no changes occur on the side of carbon dioxide emissions.

From the theoretical analysis above, both in non-condensing and condensing operating modes, carbon dioxide emissions are higher in the case of G20 gaseous fuel compared to hydrogen-enriched gas fuel, G222, respectively.

The theoretical data obtained and presented in Table 4 are extrapolated for an average annual operation of 2800 h. The density of carbon dioxide at a temperature of 0 °C is $\rho = 1.977\ kg/m_N^3$. By evaluating the values displayed in Table 5, 1.3 tons of CO_2 emissions savings are obtained, for a condensing boiler one-year operation.

Table 5. Theoretical values for carbon dioxide emissions.

Combustible Type	V_{CO_2} (m^3_N)	m_{CO2} (ton)
G222	6862.5	13.6
G20	7549	14.9

All these results presented above are obtained following a theoretical analysis that assumes that the combustion reactions are carried out stoichiometrically and the combustion is complete. However, in equipment's real-life operation, an excess air coefficient is always needed to ensure the fact that combustion is near to complete and the amount of incomplete combustion products such as carbon monoxide is as low as possible.

In the following, theoretically obtained results will be validated by experimental results.

The procedure for testing combustion equipment, respectively, a thermal power plant, in order to apply the CE marking is an extremely complex and laborious one. In carrying out the experiments, explicit specifications must be followed regarding:

- Ambient conditions—temperature, relative humidity
- The pressure of the working agents (gaseous fuel and water from the round-trip circuit of the equipment)
- The maximum limits for the various components in the combustion gases
- The establishment of a stationary work regime during a period in which the operation is monitored

The experimental research can only be carried out under conditions where the monitored parameters do not vary by more than ±0.5 °C for working agents' temperatures when taking the reference values as 50/30 °C, and with more than ±0.5% in the case of flow, according to the testing standards [14,15], for a time interval of 10 min.

The experimental values are presented in Table 6. Since the values' variation is extremely low, only the averaged values for a time interval of 10 min are presented.

Table 6. Experimental average values for the 50/30 °C condensation regime.

Combustible Type	Water Flow (kg/h)	Gas Flow, B (m^3/h)	Water Outlet (°C)	Water Inlet (°C)	CO_2 in Flue Gas (%)	CO in Flue Gas (ppm)	NO_X in Flue Gas (ppm)	Flue Gas Temperature (°C)
G222	1194	3.383	49.78	30.3	8.8	54.5	8	58.9
G20	1246	2.754	50.04	29.7	9.45	74.8	9	58

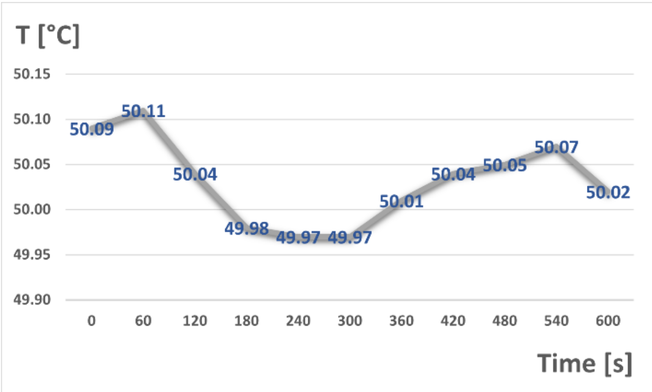
The temperature variation for the water inlet and outlet in the condensing boiler with flattened pipes during testing is plotted in the graphs presented in Figure 3, to highlight the compliance with the mandatory requests regarding fitting in the interval ±0.5 °C from the reference values.

In order to reach the range of the quasi-stationary regime, the circuit worked for around an hour until the temperatures in the system were equalized, with the help of the fully automatic adjustment system, but these values are not presented because they do not have an impact on the analysis.

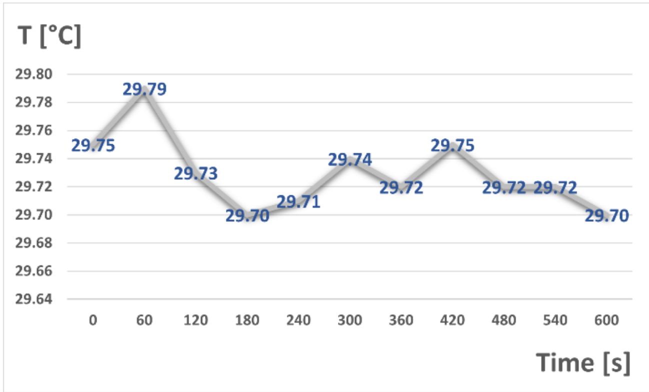
Based on experimental values, the efficiency and heat load were determined, and are highlighted in Table 7.

Table 7. Performance indicators for the 50/30 °C condensation regime.

Combustible Type	Air Excess Coefficient $\lambda(-)$	Heat Load (kW)	Efficiency $(-)$
G222	1.33	28.24	106.12
G20	1.32	28.28	105.69



(**a**)



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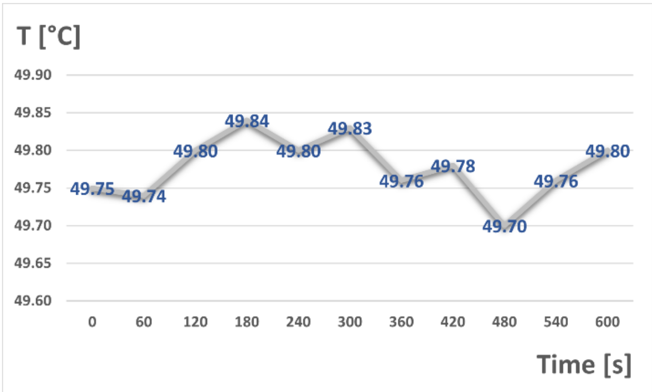

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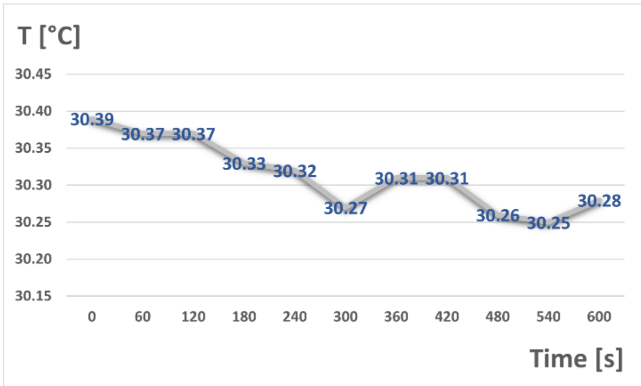

(**d**)

Figure 3. The temperature variation during testing (**a**) G20-outlet; (**b**) G20-inlet; (**c**) G222-outlet, and (**d**) G222-inlet.

4. Discussion

It should be noted that the experimental results obtained by the team members refer exclusively to the G222 fuel mixture; for different concentrations of hydrogen in the gaseous fuel mixture, further testing is to be done.

From a technological point of view, it was found that there are no constructive limitations or constraints on the burner/heat exchanger model when adding 23% hydrogen. However, research will continue, with the idea of establishing an upper limit on the percentage of hydrogen, so that operational safety problems such as flashbacks do not arise.

The most important test condition was to maintain the nominal heat load value for both G20 and G222 combustible gas.

Using the experimental results, we can evaluate with which amount the carbon dioxide emissions increase when using G20 as combustible, compared to G222. Considering the ratio between the volumes of dry flue gases from Table 8, the following coefficient results, as presented in Equation (1):

$$\frac{\left(B \cdot V_{g.dry.real} \cdot CO_2(\%)\right)_{G20}}{\left(B \cdot V_{g.dry.real} \cdot CO_2(\%)\right)_{G222}} = 1.09 \cong 1.1 \tag{1}$$

This value is consistent with the other two types of condensing boilers which were mathematically modeled in a previous paper, with corrugated pipes and finned pipes, respectively. In this way, additional validation of the results was achieved.

Table 8. Calculated values resulted from experimental testing.

Parameter	G222	G20
$V_{g.dry,\ real}\left[\frac{m^3 \text{flue gases}}{m^3\ \text{comb.}}\right]$	9.59	11.9
$V_{CO_2}\left[\frac{m^3 CO_2}{m^3\ \text{comb.}}\right]$	0.844	1.124
$m_{CO_2}\ [t_{CO_2}]$	14.95	16.21

Thus, an important conclusion could be drawn, that for any constructive model of condensing boiler with certain constructive and operating specifics, operating with G20, the reduction of carbon dioxide emissions, when using G222, can be evaluated with high accuracy, of $\pm 0.7\%$, using the ratio in Relation (1).

Based on those stated above, the authors propose the introduction of the concept of a High-Performance Condensing Boiler (HPCB). For all the condensing boilers with the features listed below that can fall into this concept of specifics, knowing the carbon dioxide emissions when operating with G20 is enough to determine the emissions in the case of using G222.

The HPCB concept was generated by the close observation of operating data from both numerical simulations and experimental records for several different solutions of condensing boilers. It was interesting to observe that, regardless of the constructive solution, the performance parameters were almost identical for a range of applications together with their response to the variation of combustible composition (namely, the addition of H_2). By reference to the detailed operating parameters from the numerical simulations for a range of constructive solutions of condensing boilers and the measuring data from their testing, an interesting conclusion was drawn: if a boiler can be considered as HPCB, then the nominal operating parameters from the overall performance point of view are similar, under acceptable engineering error conditions.

The underlying reason for this phenomenon is extensively described in the following. When the heat exchange surface is designed to insure a non-condensing efficiency of around 99% at nominal boiler thermal output and the heat exchange takes place over small characteristic lengths of the heat exchange surface, the mass transfer will cause a decrease in the flue gases' humidity down to the level of saturation corresponding to the heat exchange surface temperature. In this scenario, we can make the most of the condensation phenomenon. Therefore, for a quasi-countercurrent flow of the flue gases by report to the water circuit and for similar inlet temperatures, the flue gases at the boiler exhaust will be at dew point and at approximately the same temperature for all the high-performance condensing boilers. If the boiler is designed as previously stated, the same output parameters will result for the flue gases in terms of temperature and humidity content, thus generating nearly identical performance parameters, whatever the design solution of the heat and mass transfer surface for the same combustible and burning conditions (mainly air excess).

So, concluding, a boiler could be integrated in the HPCB concept if it is designed, such as:

- Burning process is characterized by low burning air excess coefficients;
- Heat exchange surface is over-dimensioned by a figure of 2 to 3 (by comparison to the non-condensing equivalent classical boiler) and generates sensible heat transfer efficiencies of about 98.5–99%;
- Heat exchange surfaces characterized by small characteristic lengths, mainly in the condensing section of the boiler (the one before the flue gas exhaust);
- The flue gases, at least for the most part of the boiler and necessary for the final condensing surfaces, ensures a countercurrent for the flue gases against the heated agent
- The condensation is efficiently drained, in order not to generate a film with significant thermal resistance that can rise the useful condensing dew point at the flue gases' contact with the heat and mass transfer surface.

Thus, an important statement is that for any HPCB having the same thermal load, the operational performances when using G20, G222, or other H2/CH4 mixtures will be the same as those of the other HPCB previously tested or numerically modeled, under normally accepted engineering errors. This conclusion is highly important because it can be stated that whatever the design of a condensing boiler is, if it qualifies as HPCB, it is expected to generate the same performances and the same response, specifically in terms of CO_2 emissions, as the ones already modeled or tested.

The aforementioned result only regards the boiler's heat and mass transfer behavior. The burning process is a separate issue and there is no link between heat and mass transfer performances and the behavior of a certain burner from a safety point of view. This means that even if there are good thermal functioning results for some constructive solutions when switching to H2/CH4 mixtures, every HPCB must be separately and particularly tested for burning process safety, mainly and priorly for light back conditions [22].

The experimental data differ from the theoretical values by means of excess air participation. The values obtained are extrapolated for an average annual operation of 2800 h and presented in Table 8. The density of carbon dioxide at a temperature of 15 °C (experimental evaluation) is ρ = 1.87 kg/m^3. By evaluating the values displayed in Table 8, 1.26 tons of CO_2 emissions savings are obtained, for the flattened pipes condensing boiler one-year operation, value which is in line with the theoretical value of 1.3 tons of CO_2. The difference of around 3% is related especially to the incomplete combustion products like carbon monoxide together with the gas analyzer measuring errors.

The CO_2 volume in the two studied situations was determined as a function of the real volume of dry combustion products and CO_2 percentage from Table 6 according to Equation (2):

$$\frac{(V_{CO2})_{G20/G222}}{\left(V_{g.dry,real}\right)_{G20/G222}}\cdot 100 = CO_2(\%) \tag{2}$$

5. Conclusions

The testing results obtained present the necessary accuracy and fidelity to be used as a reference for numerical models' validation and for operational database fulfillment, due to the fact that the experimental stand is EU certified for boiler testing.

By using the experimental results, we can evaluate with which amount the carbon dioxide emissions increase when using G20 as combustible, in comparison with G222. A coefficient of 1.1 was determined, meaning an approximately 10% decrease in CO_2 emissions when G20 is replaced with G222. For a 28 kW condensing boiler, the annual reduction in CO_2 emissions averages 1.26 tons, and considering the potential market for this type of boiler, the global effect is significant.

Comparing the operational testing results with other measurement data gathered from previous testing, a nearly insignificant variation for the boiler performance parameters emerged. These observations led to introducing a new concept, meaning the HPCB.

The most important benefit is that, without being necessary to test an equipment both with G20 and G222 combustion gases, if it falls under the HPCB requirements, the main operational parameters and emissions values can be determined by means of correlation factors specific for HPCB. Thus, only testing the equipment operation with G20 (in which the cost is much lower than in the case of G222) provides sufficient bases for assessment.

It must be stated that the burning process is a separate issue and there is no link between heat and mass transfer performances, strictly related to the heat exchanger's design, and the behavior of a certain burner from a safety point of view.

This paper's main objective was to evaluate the impact on CO_2 reduction when using a mixture between H_2 and CH_4 and, therefore, a reduction coefficient was only determined for this type of gas. Considering the theory behind the HPCB concept and the extended existing database made by the authors for this type of boiler, an interesting future objective is to determine coefficients also for other types of pollutants and operating performances.

In this paper, only the limit backlight gas G222 was used, and therefore, taking into account the pressing necessity of CO_2 emission reduction, higher values for the H2 concentration in the mixture will be evaluated in future research.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

B	Combustible volumetric flow $\left(Nm^3/s\right)$
V_g	Specific flue gases' volume $\left(Nm^3/Nm^3\right)$
$V_{air,min}$	Stoichiometric air volume for combustion $\left(Nm^3/Nm^3\right)$
$V_{g,dry}$	Specific dry flue gases' volume $\left(Nm^3/Nm^3\right)$
$V_{CO_2,flue\ gases}$	CO_2 gas volume as part of the dry flue gases $\left(Nm^3/Nm^3\right)$
$V_{H_2O,flue\ gases}$	H_2O gas volume as part of the dry flue gases $\left(Nm^3/Nm^3\right)$

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