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Investigation of Flow and Combustion Technology Changes in a Device Nozzle for Natural Gas as a Result of Mixing in Hydrogen

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Abstract
The efforts of the European Union (2021, EU Regulation on Gas and Hydrogen Networks) have been waiting for a solution to the problem of -even if only partial- independence from natural gas. The article shows the effects on the combustion technical parameters and equipment, if the 100% natural gas plant is replaced with a certain proportion of hydrogen. The article examines how it affects the combustion technical parameters of natural gas user equipment if the gas that feeds them is replaced by hydrogen-natural gas mixtures of different proportions. The results show that with the introduction of hydrogen, the Wobbe number decreases, and with this equipment, hydrogen can be added to the natural gas in an amount of 23 V/V% so that it meets the standards. When examining the flame propagation speed, we conclude that it is expected that the flame will not burn back at this ratio. The work promotes the progress of natural gas-hydrogen co-combustion technologies, as it examines a special part of the combustion equipment, the nozzle, and the flow engineering processes taking place in it. With the help of this model, we successfully investigated the excess air resulting from various natural gas-hydrogen mixtures in the case of a given geometry, but the model, with its mathematical additions, also proves that mixing in hydrogen generally reduces the amount of incoming air.

Keywords
hydrogen, gas, methane, mixture, Wobbe number, flame, injector

1 Introduction

Mixing natural gas with hydrogen deserves special attention in terms of energy supply and the natural gas network. There are several arguments in favor of mixing: from the point of view of environmental protection, it provides the opportunity for a cleaner combustion with a more favorable emission rate, all in such a way that the related equipment does not even have to be modified or replaced under certain conditions. In addition, mixing with hydrogen also increases the natural gas network flexibility [1]. A method of economical production and use of hydrogen is named by Leichner et al. [2], who, based on the "power-to-gas" approach. Here he reports that in the case of system-level, even short-term electrical overproduction, the overcurrent, and the equipment utilizing renewable energy sources together, it is a good application form for hydrogen production. In addition, the author says hydrogen is expected to be one of the key elements of the modern gas infrastructure. In 2022, Eames et al. [3] dealt in detail with the finite element simulation of hydrogen injected into the gas pipeline. In the study, the focus was not on the combustion behavior of the gas mixture, but on the analysis of the injection location. Here, the authors draw attention to the fact that the low molecular weight of hydrogen during mixing makes it prone to floating stratification, and their results prove that the direction of injection has an effect on the course of mixing. Their measurements are a more specific result it has been proven that the most efficient configuration for wireline delivery is injection. In accordance with the study, this article also discusses an injection configuration. In the same way, Liu and Pei's [4] study was created in relation to stratification, and according to the study, the natural gas network elements should be calibrated to low pressure and high velocity values for such mixing. In the joint research of Shanghai University and Peking University [5], the method of hydrogen transport was investigated, when pure hydrogen was mixed into the already established natural gas network. The lesson of the

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model developed here is that, in general, the mixing of hydrogen does not greatly worsen the condition of the pipe network, but a subsequent adjustment of the pressure may be necessary. In the same place, another research group specified the values for a 100 km long pipeline section [6]. Here, the authors specifically draw attention to the fact that hydrogen injection into the natural gas network also entails a drop in internal pressure (mainly due to different gas densities). Researchers from Beijing and Shanghai universities reached similar results when examining the effects of hydrogen mixing on the dynamic properties of the gas network [7].

In a comprehensive study of the legal limits for hydrogen mixing made at the University of Colorado [1], the authors establish a general limit of 20 V/V%, adding that this is a theoretical maximum, which was further reduced by the pipes and auxiliary equipment used (e.g. compressors) material and their tolerances (especially brittleness). This is complemented by the research of Birkitt et al. [8], who found that hydrogen mixing above 20 mol% the effects of ratio on the distribution network were investigated.

Practical measurements were carried out by researchers at the University of California [9] on a household gas oven. This study already included the Wobbe number, but primarily looked at ignition timing, burner temperature, emissions, and primary air intake behavior. A lesson learned from these measurements is that mixing hydrogen reduces the ignition time, and that even a hydrogen mixing ratio of 10 V/V% increased the temperature of the burner used for the measurement by 63%. Comparability is facilitated by the fact that we used similar mixing ratios in this article as well. The addition of hydrogen did not change NOX emissions, but reduced carbon monoxide emissions. The effect of hydrogen injection on gas engines was investigated by Wahl and Kallo, and they found that green (when electricity from renewable energy sources is used in the water splitting stage of hydrogen production) and blue (carbon dioxide-based process, with steam reforming) hydrogen supply chain are also promising substitutes for these devices gas is hydrogen [10]. Supplementing natural gas systems with hydrogen also appears in the research of de Vries et al. [11]. The Wobbe number calculation appears in the article as a basic calculation of the interchangeability of gases. The authors also emphasize that an economical and competitive way to store excess energy from renewable energy sources is hydrogen technology [11]. A similar position is expressed by the research group of the University of Florence [12], which modeled the path of hydrogen from a renewable energy source. Tests were carried out with household combustion equipment and engines at the University of Rome [13], where the Wobbe number limit was considered at 20 V/V%, but the measurements were performed up to 30 V/V%. Here, in the case of hydrogen leakage, authoritative ATEX regulations are highlighted, with compliance with which up to 20% mixing, household appliances do not need to be replaced.

This article examines how the combustion parameters of natural gas-powered equipment are affected by replacing natural gas with hydrogen-natural gas mixtures of different proportions. It should be noted that in both simulations and calculations, natural gas was approximated with pure methane gas, not as a gas mixture. We also examine the controllability of the injector's performance and excess air factor. For this purpose, we describe the method of controlling the excess air on a specific injector model. On the same model, we examine what the appropriate ranges of excess air are for various mixtures. We use calculations to determine how the laminar flame propagation speed changes at which mixing ratios, thus we can conclude at which parameters there is a risk of flashback, which can be avoided with precise planning. The values used for the calculations were taken at 0 °C, because the definition of the Wobbe number is also interpreted at the density measured at 0 °C (Table 1) [9, 14–17].

The Wobbe number, which can be calculated by the quotient of the calorific value and the root of the relative density [18], shows how much heat flows through a given cross-section in a combustion device, and for this very reason it can be rephrased and evaluated as a guiding parameter of the interchangeability of gases. This value has limits fixed in the standard. According to the current MSZ EN 1648: 2016 gas standard, the minimum upper

Table 1 Used data for methane and hydrogen [9, 14–17]

	Methane	Hydrogen
GCV [MJ/kg] [14]	55.5	141.7
NCV [MJ/kg] [14]	50	120
GCV [MJ/m^3] [14]	39.8	12.7
NCV [MJ/m^3] [14]	35.8	10.8
Density [kg/m^3] (at 0 °C, 1 bar) [15]	0.716	0.09
Lower explosion limit [%] [15]	5	4
Upper explosion limit [%] [15]	15	75.6
Adiabatical flame temperature [K] (stoichiometric mixtures) [16, 17]	2210	2400
Lower Wobbe number [MJ/m^3] [9, 17]	45.4	38.758
Upper Wobbe number [MJ/m^3] [9, 17]	50.4	45.88

Wobbe number (calculated with HHV) is 45.66 MJ/m^3 and 54.76 MJ/m^3. This is the reason why (as can be seen from later calculations in the article) the ratio of hydrogen gas is currently maximized at 23 V/V%, since this value belongs to the upper Wobbe number limit.

The modified Wobbe number considers the lower calorific value, but the temperature of the mixture is also included in the denominator, since the amount of energy flowing through the cross section depends on the gas temperature [19].

The excess air factor can be calculated by the ratio of the air available for combustion to the amount of air required for perfect combustion. Most combustion equipment, including household equipment, can be regulated in terms of excess air. In this particular case, the threaded connection on the nozzle allows us to narrow the cross-section of the fresh air inflow closer to the end of the closed mixing pipe. In this case, we limit a combustion condition, i.e. in the end, we control the degree of premixing.

The stoichiometric air requirement is the amount that the fuel uses for its complete and perfect combustion [20] under ideal conditions. This is also called the theoretical air requirement [21]. The practical air requirement is usually higher than this, since the perfect combustion of the gas in practice (mainly due to imperfect mixing) requires more air than the theoretically required amount. This concept the amount of real air taken in, which does not directly depend on the combustion process, is influenced by purely local flow factors (gas mixture velocity, pressure, cross-section, etc.).

The laminar flame propagation speed of hydrogen significantly exceeds that of methane (Table 1), as a result, the higher the proportion of hydrogen involved in the combustion, the higher the flame propagation speed of the mixture will be. The flame spread knowing the speed is also important because, among other things, it determines whether flashback is expected [22]. During flashback, the flow velocity measured in the cross-section in front of the burner is lower than the flame propagation velocity. This speed can be calculated as the product of the sinus of the half-cone angle measured in the flame peak (Fig. 1) and the average speed of the unburnt mixture [23].

This article complements the above studies by considering a critical part of the equipment, the injector and the flow processes taking place in it.

2 Finite element model and verification calculation

The calculations are illustrated on the injector of an air heating system. The parts of the model (as shown in Figs. 2 and 3) are a nozzle (confusor) and a threaded mixing tube. Angular incisions on this pipe ensure the supply of combustion air, and by moving the injector along the thread in the mixer, the cross-section available for the incoming fresh air can be adjusted (Figs. 2, 3). For the finite element calculations, we created a CAD model of the flow field in the injector, and the calculations were performed on its elementary cells. The global element size: 1 mm, locally the mesh was compressed around the nozzle and wall surfaces and at the air inlet (4 inflation layers). At the inlet, the inflowing gas has an adjustable composition, different proportions of incoming natural gas and hydrogen can be specified. The displacement of the gas mixture entering here is caused by a standard overpressure of 25 mbar in the gas pipelines. The mixture arriving at the inlet is called the mixture hereafter. The fresh air inlet can be seen on the side (Fig. 3, "Air inlet" surface). When approaching the air inlet surface, the concentrated jet is fast compared to the speed experienced at the inlet, so the pressure of the medium decreases. Compared to the initially stationary medium at the air inlet, the pressure of the concentrated jet is lower, so the air moves towards the lower pressure and continues

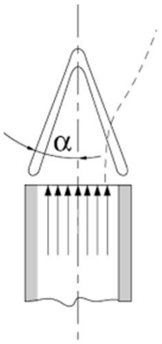


Fig. 1 Flame front simplified section [23]

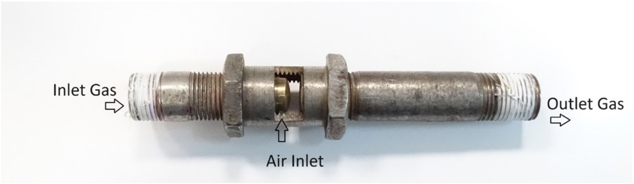


Fig. 2 Sample model in real

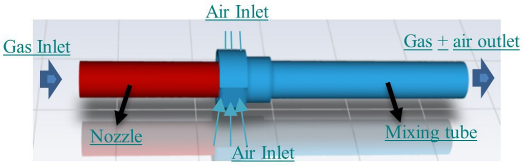


Fig. 3 Parts of sample model

to flow with the gas mixture. The internal surfaces have a general roughness in mechanical engineering, and we also took into account the force of gravity. Initially, the position of the nozzle is such that it leaves half of the fresh air opening free. The advantage of the model is that it is universal in terms of gas mixture, any ratio can be authentically tested with any incoming gas mixture.

In our preliminary calculations, we wrote down the Bernoulli equations at the points of the inlet, the nozzle and the air inlet (Fig. 4), and also included the continuity equations to form a system of equations. The most important question was the velocity conditions prevailing in the nozzle. Knowing the size of the cross-sections and the pressure of the gas line, the gas velocity at the inlet (v_1) and in the nozzle (v_2) can be calculated.

The calculations were written for the air inlet cross-section and the mixing tube in a similar system.

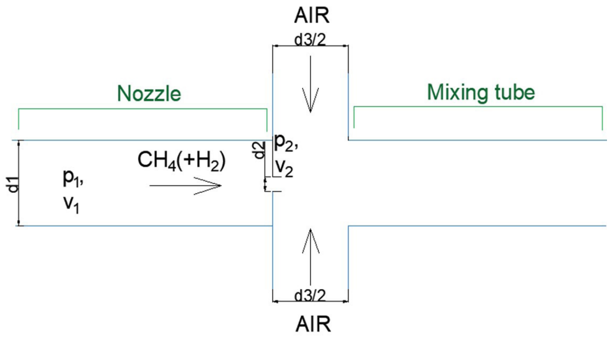


Fig. 4 Simplified model for manual calculation (d_1: inlet diameter, d_2: confusor diameter, $d_{3,1}$: air inlet on the upper side, $d_{3,2}$: air inlet on the bottom side ($d_{3,1} = d_{3,2}$))

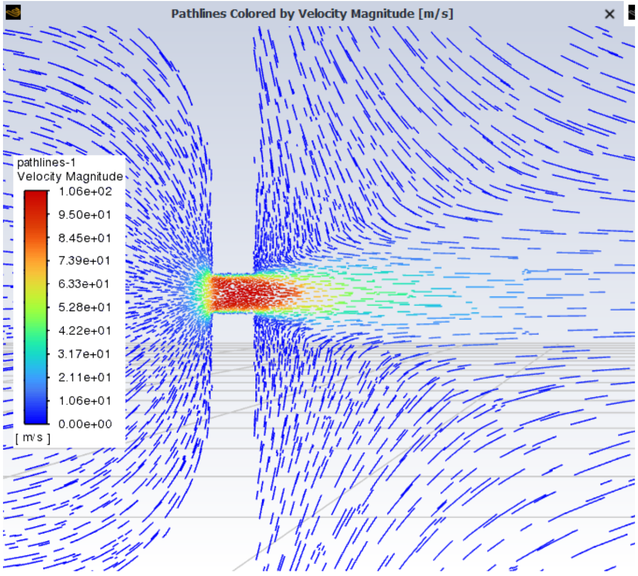


Fig. 5 Velocity vector symbols at the narrowing cross-section

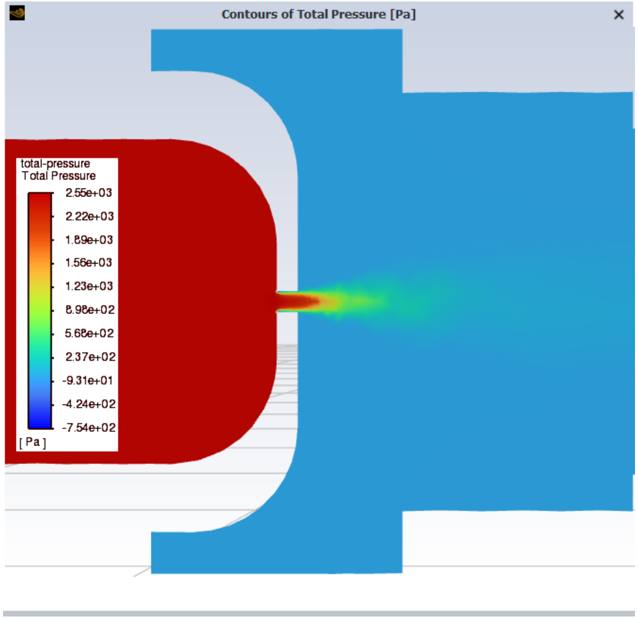


Fig. 6 Total pressure at the nozzle

The results of the simulations (Figs. 5 and 6) and the manual calculations (Fig. 4) show a difference of 3%. This is mainly due to the fact that the finite element model also takes into account the Borda-Carnot loss [24]. This occurs when the flow reaches a cross-section that is significantly smaller compared to the previous cross-section. This occurs at two points, on the one hand between the inlet and the nozzle, and on the other hand between the air space and the air inlet. Additional losses that the model takes into account, but manual control does not, are losses caused by eddies. Such vortices are mainly seen at the fresh air inlet. The solution principle of the finite element model is the solution of the Navier-Stokes equations. During the calculation, the environmental parameters of the model were left unchanged, only the hydrogen-methane ratio of the input mixture was changed between the different experiments.

3 Presentation of experimental equipment

In order to validate the results, we built an experimental system, the purpose of which is to test the values measured in the simulation. The elements of the system (moving along the line from the left side of Fig. 7) natural gas tank, tap, volume flow meter, pressure gauge ("U" tube manometer, standing), injector, pressure gauge (manometer, horizontal, higher accuracy), second volume flow meter and connected to the end of the system glowing grid.

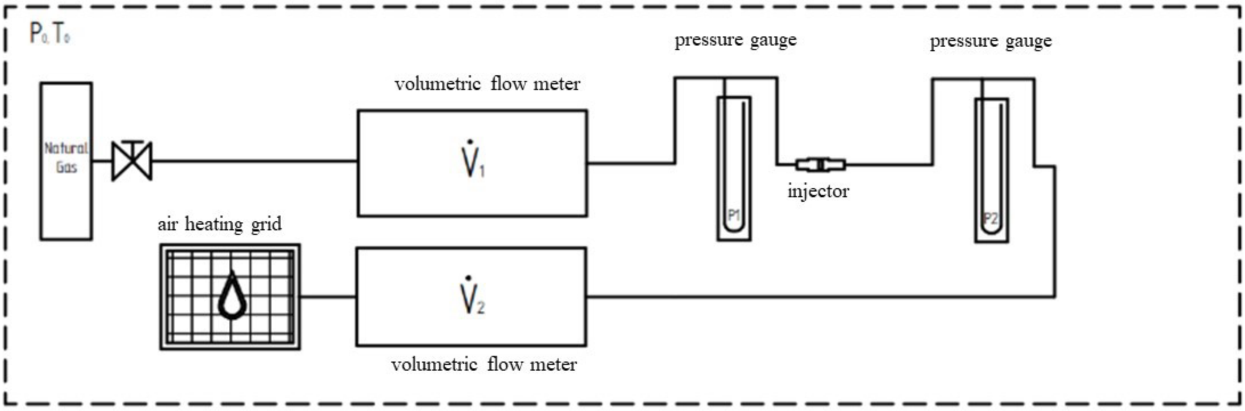


Fig. 7 Measuring system

4 Theoretical background, changes in combustion technical parameters with the addition of hydrogen

With the gradual addition of hydrogen to methane, the density of the mixture decreases (Fig. 8). The mixing volume ratio of hydrogen was varied between 0 V/V% and 47 V/V%. When choosing the range, it was important that the measurement exceeds the standard mixing ratio of 20 V/V% according to our preliminary calculations by a large percentage, and that the mixing limit corresponding to the Wobbe number should definitely fall within the measurement range. This is especially interesting because of the later Wobbe number calculation, but it also plays a role in the flow inside the pipe: Bernoulli's equation also implies that the same pressure difference from the rarer gas moves a smaller volume. The development of the total calorific value follows from the calorific value of the components taken individually with mixing.

5 Practical air demand and excess air

The mechanical design of this injector creates a direct connection between the theoretical air requirement and the intake air volume: this injector is designed in such a way that the cross-section available for the intake air can be adjusted along the threaded stem. The amount of inhaled air and the mass flow of the inhaled gas initiated by the pressure difference (25 mbar) were provided by the finite element model (Ansys Fluent).

According to the results of the finite element Fluent test, the intake air gradually decreases with a gradual increase in the amount of hydrogen (Fig. 9). This can be attributed to the low density and specific volume of hydrogen.

The excess air factor was examined in the case of the half-open state, but the trend is true in all positions: with the addition of hydrogen, the excess air increases at a slight rate (Fig. 10), since the combustion air requirement of H_2 is much less than that of methane, the amount of air taken in and compared to this, it decreases at a slight pace.

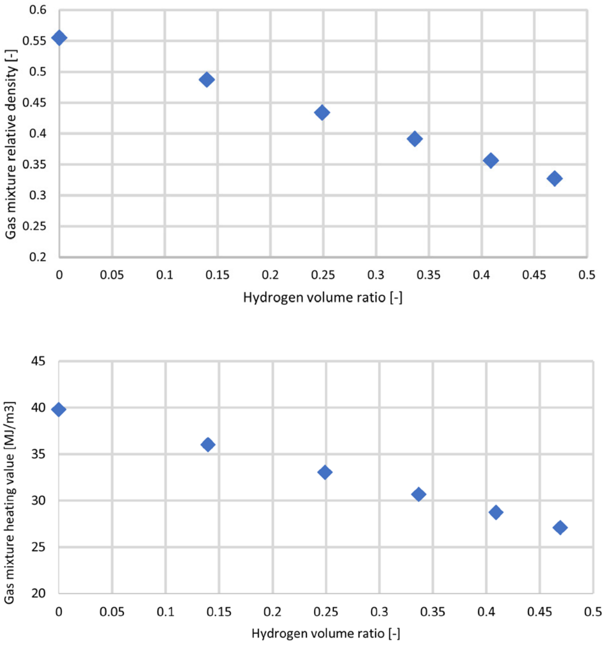


Fig. 8 Change of relative density and heating value with hydrogen volume ratio

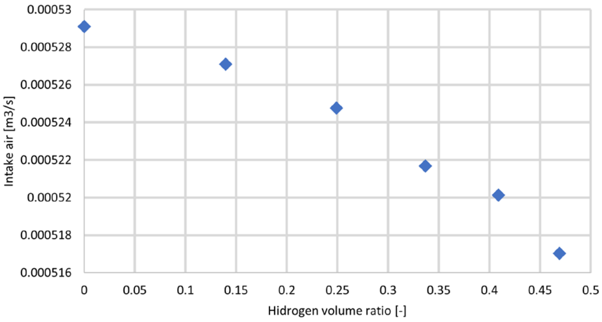


Fig. 9 Intake air in relation of hydrogen ratio

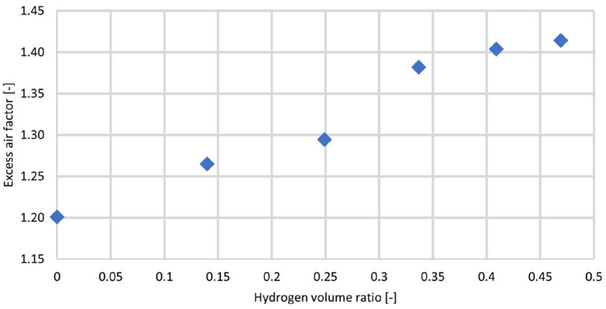
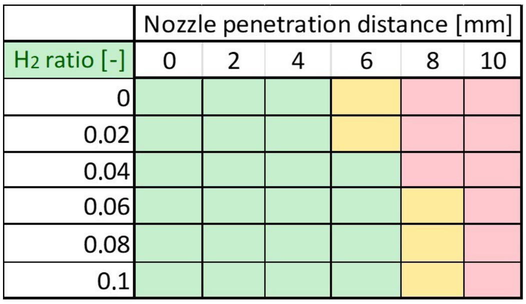


Fig. 10 Excess air factor in relation of hydrogen ratio



	Nozzle penetration distance [mm]					
H2 ratio [-]	0	2	4	6	8	10
0	🟩	🟩	🟩	🟨	🟥	🟥
0.02	🟩	🟩	🟩	🟨	🟥	🟥
0.04	🟩	🟩	🟩	🟩	🟥	🟥
0.06	🟩	🟩	🟩	🟩	🟨	🟥
0.08	🟩	🟩	🟩	🟩	🟨	🟥
0.1	🟩	🟩	🟩	🟩	🟨	🟥

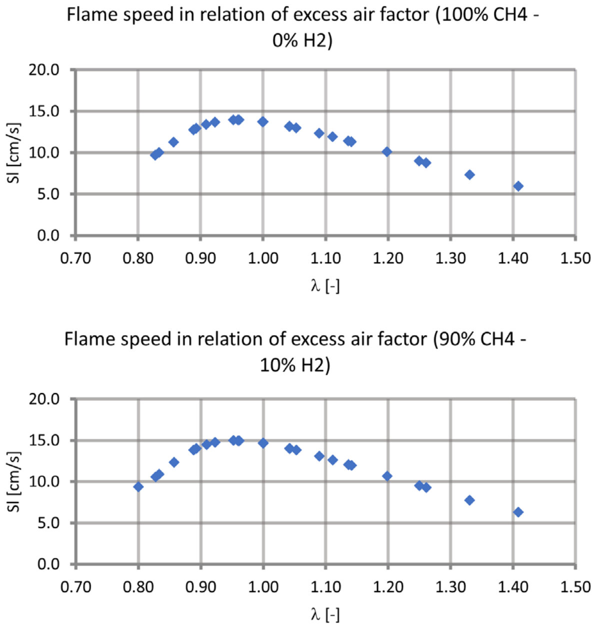
Fig. 11 Nozzle penetration distance: Green = Excess air factor is acceptable, Yellow = Excess air factor is close to the acceptable, Red = Excess air factor is not acceptable

6 Adequacy of the injector and controllability of excess air

The lesson of the simulation and the manual calculation is that, when examining different gas mixtures with the same injector, this cross-section must be kept within different limits depending on the mixture (a fully exposed, 12 × 20 mm cross-section is the fully open position, and the closed state means the completely blocked path for the air from). By increasing the proportion of hydrogen, the amount of theoretically necessary air decreases, so in the pre-mixing stage, for the value of the excess air factor corresponding to methane, the largest cross-section should be left free for the inflow of air in the case of pure methane. For example, if the target value is the excess air factor of 1.2, and we know that in the half-open position the amount of air taken in for pure methane is 5.46×10^{-4} m^3/s, then the required amount of air for premixing is 5.76×10^{-4} m^3/s. If we take a linear relationship between the amount of air taken in and the free surface of the intake opening (continuity equation), then with a fixed width of 20 mm, the distance between the nozzle and the mixing tube is ideally 6.5 mm. This is also confirmed by the fact that the injector and the mixing pipe were set at this distance in the factory settings of the natural gas-powered test equipment. In a broader sense, the lesson is that in the case of feed gas exchange, care must be taken to ensure that the excess air control matches the changed combustion air requirement. In practice, however, the installation is fixed, and it is not realistic to regulate the excess air on the injector as a user in the event of a change in the composition of the incoming gas. For this reason, it is more instructive to examine different gas compositions in terms of excess air at a given position (Fig. 10). Since the excess air factor can be regulated mechanically, we can also establish a limit for how long the nozzle can be screwed into the mixing pipe for various gas mixtures, i.e. how much of the fresh air inlet can be covered. The various nozzle insertion distances are summarized in the three-color table (Fig. 11). Red color indicates the case when the excess air is below 1, so the flame will not be fully premixed when set. Yellow color indicates excess air above 1 but below 1.2 (slightly lean mixture on fuel), and green indicates the case when the mixture is lean on fuel.

7 Flame speed, flashback

Between the two endpoints of the measurement range (0 V/V% H_2 and 47 V/V% H_2) (Fig. 12) examining the gas mixture for flame propagation speed with the GRI-Mech. ver 3.0 mechanism, it can be said that at points belonging to the same excess air factor, the flame speed increases with the addition of hydrogen, but there is no danger of flashback in the range of the Wobbe number allowed in the standard. The fact that the flame speed increases with the addition of hydrogen is expected to be easily observed even at higher mixing ratios, since the normal flame speed of hydrogen gas is much higher than that of



Flame speed in relation of excess air factor (100% CH4 - 0% H2)

Flame speed in relation of excess air factor (90% CH4 - 10% H2)

Fig. 12 Flame speed at different hydrogen ratios methane. As the flame speed increases, the alpha half-cone angle visible in the introduction increases, the flame becomes "flatter". By increasing the angle, after a limit value, the gas burns back.

8 Wobbe number and modified Wobbe number

It can be seen (Fig. 13) that the Wobbe number decreases with the addition of hydrogen in the investigated range. Considering the currently standard Wobbe number limits, the possible theoretical maximum mixing ratio is 23 V/V% hydrogen. However, it is worth adding that this Wobbe number limit refers to the 2H [25] gas group (MSZ 1648 separates two gas groups based on composition based on the Wobbe number, one of which is 2H (its Wobbe number ranges from 45.66 to 54.76 MJ/m^3). Residential gas appliances are also uniformly designed to burn gases belonging to these gas groups.), of which only pure methane is a member of the recorded measurement points, so it cannot be applied to the hydrogen-methane mixture in a strict sense. However, if we start from the interchangeability of the gases, it is definitely worth examining the Wobbe number of the gas mixture in this way, since in the case of a changed fuel in a household combustion device, the amount of heat released is only the same if the Wobbe numbers of the starting gas and the new gas are also the same. The practical significance of this is that one of the sizing parameters of combustion equipment is the amount of heat released during combustion, and the interchangeability of the feed gases is ultimately important for the integrity of the construction and the lifetime of the equipment [26]. For this reason, it is of practical importance to evaluate the hydrogen-methane mixture in the same Wobbe number range as the 2H gas group.

It is also interesting to observe the modified Wobbe number (Fig. 14), which enables the comparison of the volumetric energy content of various heating gases. It can be seen (Fig. 13) that the Wobbe number decreases with the addition of hydrogen in the investigated range. Considering the currently standard Wobbe number limits, the possible theoretical maximum mixing ratio is 23 V/V% hydrogen. However, it is worth adding that this Wobbe number limit refers to the 2H [25] gas group, of which only pure methane is a member of the recorded measurement points, so it cannot be applied to the hydrogen-methane mixture in a strict sense.

It is also interesting to observe the modified Wobbe number (Fig. 14), which enables the comparison of the volumetric energy content of various heating gases.

It can be seen that the mixing of hydrogen gas can be solved technically, it does not impair the combustion properties, in fact, it is chemically bound energy entered with fuel. In addition, the lessons learned from the Wobbe number calculations are suitable up to a certain volume percentage for the operation of household combustion equipment when mixed with natural gas. It should be noted, however, that mixing has several other limitations. This article carried out the tests from the side of the equipment, but the preparation of the network is also important, since the regulation of the flow rate and gas pressure can be a challenge [27, 28], in addition to the material of the transport modules, since the mixing of hydrogen increases the risk of damage due to embrittlement [29].

9 Experimental results

The measurement serves to verify the Fluent model, so it is advisable to carry out tests with 100% methane. If the system produces the same results as the computer model in these tests, it can be said that the test created in Ansys Fluent is suitable for later testing other injector geometries and other gases and gas mixtures.

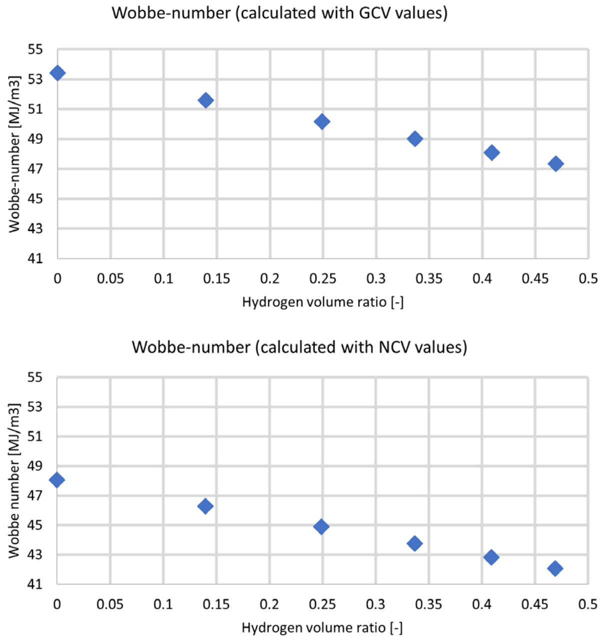


Fig. 13 Change of Wobbe number in relation of hydrogen ratio

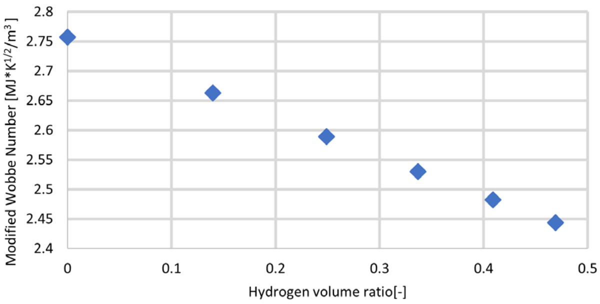


Fig. 14 Change of modified Wobbe number in relation of hydrogen ratio

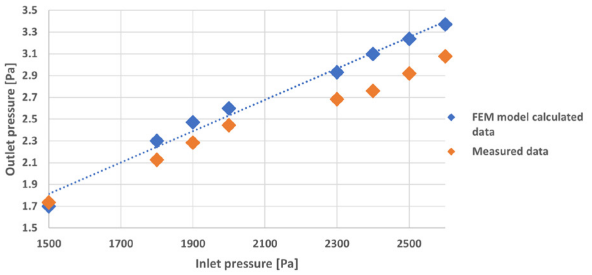


Fig. 15 Measured and calculated above-athmospheric pressure data the outlet

In the case of 100% methane, the real measurement and the data measured in Ansys showed a difference of 2–12%, this difference indicates an acceptable model (mainly, becouse the Ansys model calculates with a constant enviromental temperature value, but the experience was performed with slight warming enviroment). At the beginning of the measurement, we assumed that the inlet pressure shows a linear relationship with the outlet pressure under the same material and conditions. According to experience (Fig. 15), this graphically differs from the assumed straight line in some cases. This can be partly attributed to the warming of the environment, the heating of the system, and to a small extent to the humidity fluctuation between the recorded points.

10 Conclusion

By mixing hydrogen with natural gas, the density of the gas mixture decreases, and the rarer gas mixture carries less air with it in the injector. At the same time, however, the excess air shows a decreasing trend, the reason for which is that the theoretical combustion air requirement of the mixture decreases by increasing the mass ratio of hydrogen in the gas mixture.

We have also proven that even in the case of hydrogen mixing, the mechanical control plays an important role in the injector due to excess air, and we emphasize that in the case of a gas change, in addition to the Wobbe number, it is also necessary to check whether the injector setting matches the changed combustion air requirement, because in some cases this may need correction.

It was possible to create and verify with experiments a finite element model suitable for injector testing, which is useful for testing different, arbitrary gas mixtures, as well as for testing other injector geometries with small modifications.

In terms of flame propagation speed, it can be said that at points with the same excess air factor, the flame propagation speed increases with the addition of hydrogen, but there is no danger of flashback in the permissible Wobbe number range.

We found that although the Wobbe number decreases with the increase of the volume ratio by mixing in hydrogen, we still comply with the law with a volume ratio of 23 V/V%.

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