

The Effect of Initial Pressure on Explosions of Hydrogen-Enriched Methane/Air Mixtures

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Hydrogen-enrichment has been proposed as a useful method to overcome drawbacks (local flame extinction, combustion instabilities, lower power output, etc.) associated to turbulent premixed combustion of natural gas in both stationary and mobile systems. For the safe use of hydrogen-enriched hydrocarbon fuels, explosion data are needed. In this work, experimental tests were performed to evaluate the explosion parameters for stoichiometric hydrogen-methane blends in air, with the hydrogen molar content in the fuel varying from 30 % up to 70 %, at different initial pressures (1, 3 and 6 bar). Results allow quantifying the combined effects of hydrogen presence and initial pressure on maximum pressure, maximum rate of pressure rise and burning velocity.

1. Introduction

The safe use of hydrogen-enriched hydrocarbon fuels requires the knowledge of explosion parameters. Maximum pressure, maximum rate of pressure rise and burning velocity are the most important parameters for the assessment of process hazards and the safe design of process equipment.

Di Sarli and Di Benedetto (2007) have computed the laminar burning velocity of hydrogen-methane/air mixtures at different fuel compositions, fuel/air ratios and pressures. Results show the ability of a Le Chatelier's rule-like formula to reproduce the calculated burning velocities.

More recently, we have presented experimental results of explosion tests for stoichiometric hydrogen-methane/air mixtures with 10 % of hydrogen molar content in the fuel (Cammarota et al., 2009). Tests were carried out in a 5 l closed cylindrical vessel starting from different initial pressures (1 - 6 bar). The hydrogen presence has weak effects on the burning velocity and the maximum pressure, and stronger effects on the maximum rate of pressure rise.

In this work, a larger set of experimental data is presented for stoichiometric hydrogen-methane/air mixtures, with the hydrogen molar content in the fuel varying up to 70 %, at different initial pressures (1, 3 and 6 bar). The predictive capability of Le Chatelier's rule-like formula is also tested.

2. Experimental apparatus

The experimental set-up has been described previously (Camarota et al., 2009). It consists of a 5 l closed cylindrical chamber tested for explosion up to 400 bar (Figure 1).

A KSEP 320 transformer (220-230 V and 50 Hz with 25.0 kV discharge current) was used for central spark ignition. A large fraction of energy was dissipated and it was not possible to determine the energy actually deposited in the spark gap.

The mixture composition was obtained by the partial pressure method, starting from vacuum conditions. The initial temperature was set to 300 K for all tests.

The pressure history was measured by means of a Kulite pressure transducer (ETS-1A-375 series M). The sample frequency was 100 kHz.

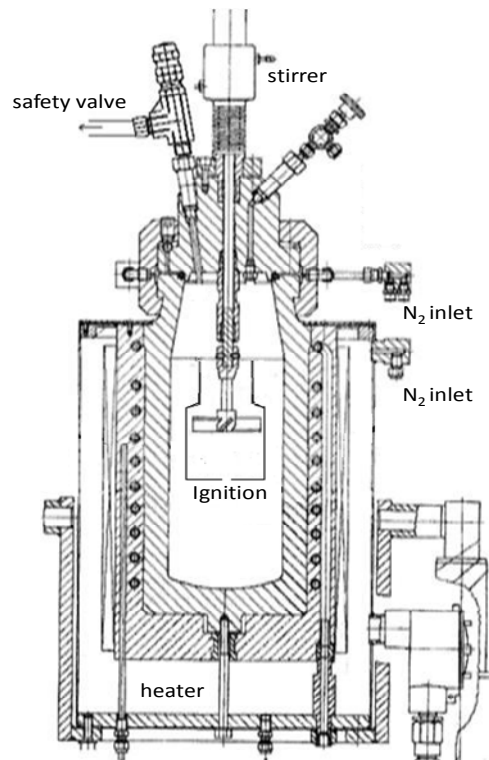


Figure 1. The experimental set-up.

3. Results

The values of mixture composition and initial pressure adopted in the explosion tests are reported in Table 1. The molar ratio of hydrogen over total fuel (methane plus hydrogen), λ , was varied from 0.3 to 0.7. The fuel/air ratio was set to the stoichiometric value for all tests. The initial pressure was varied from 1 to 3 and 6 bar.

Table 1. Mixture composition and initial pressure (P°) used in the experimental tests. λ is the molar ratio $H_2/(H_2+CH_4)$

λ v/v	CH₄ % v/v	H₂ % v/v	Air % v/v	P[°] bar
0.3	8.4	3.6	88.0	1
0.3	8.4	3.6	88.0	3
0.3	8.4	3.6	88.0	6
0.5	7.2	7.2	85.6	1
0.5	7.2	7.2	85.6	3
0.5	7.2	7.2	85.6	6
0.7	5.4	12.7	81.9	1
0.7	5.4	12.7	81.9	3
0.7	5.4	12.7	81.9	6

Figures 2 and 3 show the pressure time histories for explosions of hydrogen-methane/air mixtures with λ equal to 0.3, 0.5 and 0.7, at initial pressure of 1 bar (Figure 2) and 6 bar (Figure 3).

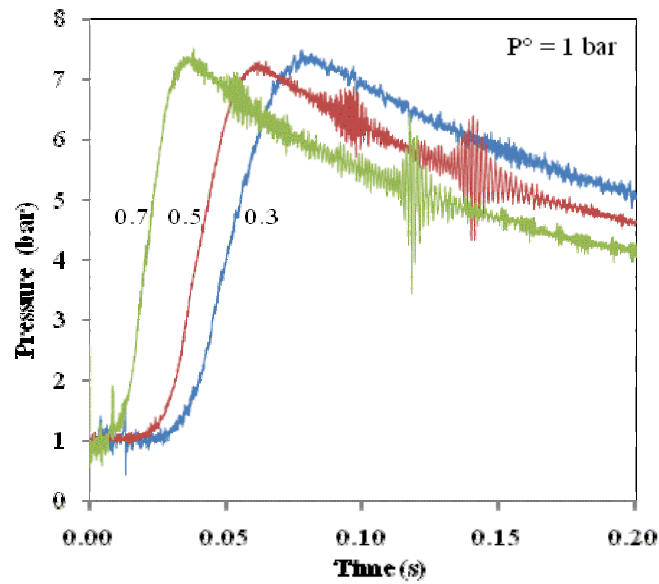


Figure 2. Pressure time histories for explosions of stoichiometric hydrogen-methane/air mixtures with λ equal to 0.3, 0.5 and 0.7, at initial pressure of 1 bar.

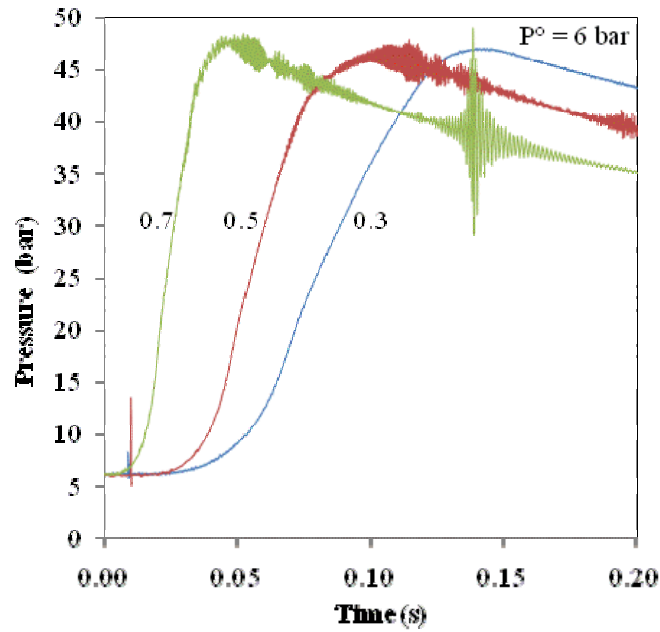


Figure 3. Pressure time histories for explosions of stoichiometric hydrogen-methane/air mixtures with λ equal to 0.3, 0.5 and 0.7, at initial pressure of 6 bar.

For all tests, Table 2 summarizes the measured maximum pressure (P_{\max}), maximum rate of pressure rise $(dP/dt)_{\max}$ and time corresponding to the pressure peak (t_d).

Table 2. Maximum pressure (P_{\max}), maximum rate of pressure rise $(dP/dt)_{\max}$ and time corresponding to the pressure peak (t_d) for all experimental tests

λ v/v	P° bar	P_{\max} bar	$(dP/dt)_{\max}$ bar/s	t_d s
0.3	1	7.37 ± 0.10	30.72 ± 1.7	0.0785
0.3	3	22.78 ± 0.20	59.54 ± 1.7	0.0622
0.3	6	47.10 ± 0.10	82.14 ± 3.6	0.0368
0.5	1	7.26 ± 0.07	31.98 ± 2.5	0.1049
0.5	3	22.73 ± 0.04	74.80 ± 1.7	0.0814
0.5	6	47.66 (1 test)	228 (1 test)	0.0364
0.7	1	7.37 ± 0.10	30.72 ± 1.7	0.1425
0.7	3	22.86 ± 0.01	138.55 ± 4.4	0.1061
0.7	6	47.72 ± 0.30	252.69 ± 4.2	0.0459

4. Discussion

The increase of the maximum pressure with the initial pressure corresponds to the increase of the maximum adiabatic pressure. Negligible differences are observed on increasing the hydrogen content, given that all mixtures are at stoichiometric fuel/air ratios.

The effect of the initial pressure on the maximum rate of pressure rise is by far more clearly evident for any hydrogen/methane concentration. The role of the hydrogen presence in the blend is negligible with respect to the rate of pressure rise for $\lambda < 0.5$, whereas it grows distinctly for higher concentration of hydrogen. These findings confirm previous conclusions drawn in Cammarota et al. (2009) and Di Sarli and Di Benedetto (2007).

For all compositions and initial pressures reported in Table 1, we have calculated the laminar burning velocity (S_u) from the pressure time history. Details of the calculation mythology are reported elsewhere (Cammarota et al., 2009). Results are shown in Figure 4 together with the values of S_u obtained by using a Le Chatelier's rule-like formula at 1 bar (Di Sarli and Di Benedetto, 2007).

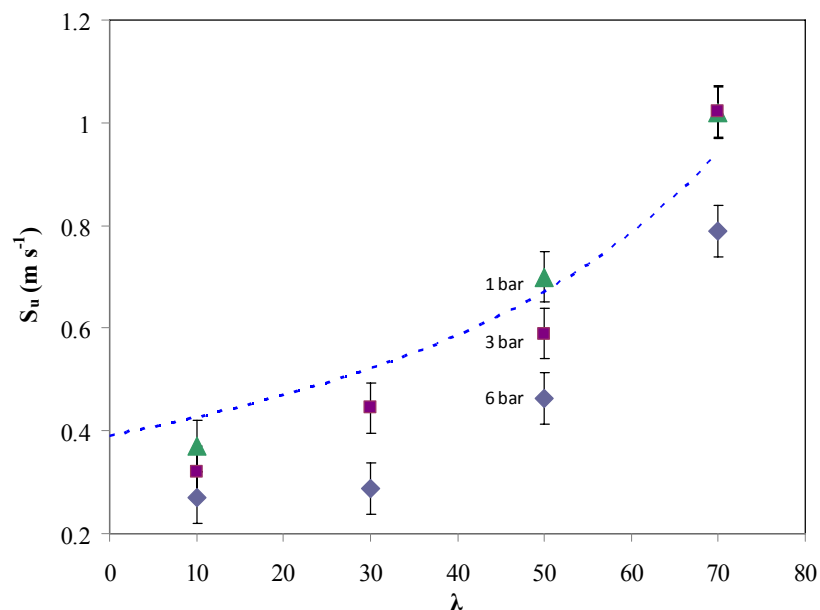


Figure 4. Laminar burning velocity (S_u) calculated from the pressure time history versus the hydrogen content in the fuel, λ , at different initial pressures. The dotted line represents S_u as calculated by Le Chatelier's rule-like formula at 1 bar. The data for $\lambda = 10\%$ come from Cammarota et al. (2009).

The laminar burning velocity decreases on increasing the initial pressure. Furthermore, Le Chatelier's rule-like formula reproduces the S_u trend.

Figure 5 shows the ratio of the laminar burning velocity calculated from the pressure time history (S_u) to the laminar burning velocity of methane (S_u^0) versus the hydrogen content in the fuel, λ , at different initial pressures. Whatever the initial pressure, no dramatic effects are observed up to 50% of hydrogen molar content. Furthermore, the S_u/S_u^0 trend with the initial pressure is opposite to the S_u trend of Figure 4. Indeed, the S_u/S_u^0 ratio increases on increasing the pressure from 1 up to 6 bar. On the other hand, the S_u/S_u^0 trend (at 1 bar) can be predicted by Le Chatelier's rule-like formula.

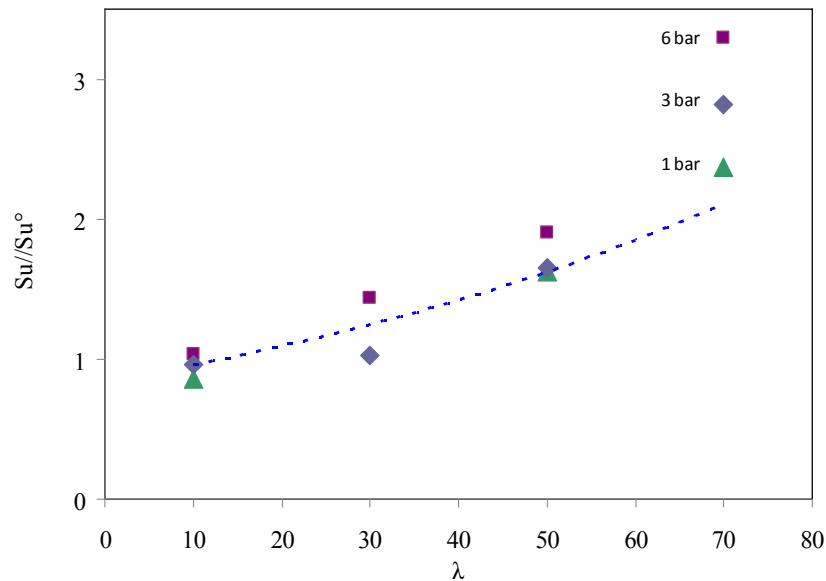


Figure 5. Ratio of the laminar burning velocity calculated from the pressure time history (S_u) to the laminar burning velocity of methane (S_u^0) versus the hydrogen content in the fuel, λ , at different initial pressures. The dotted line represents the S_u/S_u^0 ratio as calculated by Le Chatelier's rule-like formula at 1 bar.

Conclusions

Whatever the initial pressure, the effect of the hydrogen presence in the hydrogen-methane blends is relevant in terms of both, maximum rate of pressure rise and laminar burning velocity, only at hydrogen molar contents in the fuel higher than 50 %. This effect increases on increasing the initial pressure.

Le Chatelier's rule-like formula reproduces the laminar burning velocity for hydrogen-methane blends.

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