Admixture of Hydrogen to Pipelines - Experimental work on DDT without obstacles

Arnas Lucassen*, Enrico Tampieri*+, Stefan H. Spitzer*, Ernesto Salzano+
*Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Lower Saxony, Germany
+Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, Università di Bologna, Bologna, Italy

1 Introduction

In the transition to a zero-carbon-dioxide emission society, the addition of hydrogen to the gas grid system is one crucial step to replace methane partially. At the moment the hydrogen content is limited to 20 $\%_v$ [1], but it is discussed whether this amount can be increased further. The common safety characteristics of hydrogen-methane-air mixtures were investigated in recent years by the current authors [2-5], in terms of laminar burning velocity, flammability limits, and other essential parameters, confirming that methane dominates the combustion regime up to about 50 $\%_v$ of hydrogen even if the addition of hydrogen dramatically reduces the reaction zone thickness. However, no studies have addressed the analysis of the deflagration to detonation transition (DDT) and, more specifically, the effect of the hydrogen addition on the run-up distance and the cell size of the methane-air mixtures.

Some authors have investigated the DDT of hydrogen-methane-air mixtures in a tube filled with square orifice plates. Experiments with an ignition source that triggered a detonation were also performed to observe the cell sizes and whether a detonation in methane alone runs further or dies out after a while [6-8]. However, to the authors' knowledge, few experiments were conducted on an unobstructed, smooth tube filled with hydrogen-methane-air mixtures at different concentrations.

The investigations in this work are the start of several experiments to obtain experimental data aiming at defining run-up distances, and hydrogen/methane fractions for safety measures and calculations of possible DDTs.

Correspondence to: arnas.lucassen@ptb.de

2 Experimental Setup

The experimental setup consisted of a steel tube with a diameter of 50 mm and an overall length of 6.2 m. It was equipped with a high voltage induction spark as an ignition source and the gas inlet on one side and a relative humidity sensor and the outlet valve on the other side. A temperature sensor was also added 0.45 m away from the outlet valve. In total six photodiodes and piezoelectric, pressure sensors were installed at the positions displayed in Figure 1. An additional pressure sensor was added on the inlet side to adjust the beginning pressure. The tube was also equipped on the outside with a heating coat to always have a beginning temperature of 20°C.

Before each experiment, the tube was flushed with dry air to exhaust all the reactants and the moisture produced by the combustion. A maximum value of 5 % rel. humidity was chosen as a threshold to begin the injection of the hydrogen-methane-air mixture.

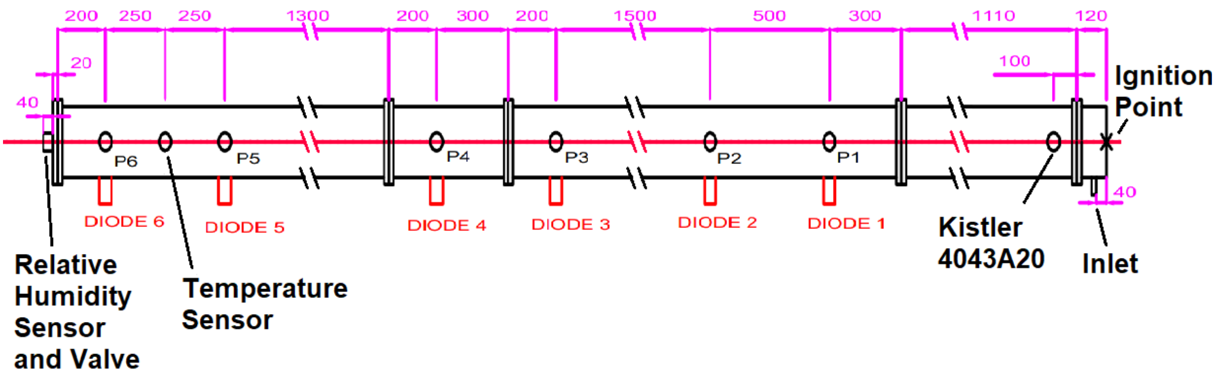

Figure 1: Schematic of the setup used in this work for the DDT tests

Once the exact percentages were entered, the system was able to provide the exact reagent flow at the inlet considering a total volumetric flow of 60 L/min. This means that the volume is flushed approximately 50 times by the mixture w for each experiment, given a preparation time of 10 minutes.

The hydrogen fraction was varied from 100% hydrogen to 100% methane, considering that the transition from deflagration to detonation occurs mainly around values of 80% hydrogen. The overall equivalence ratio λ was kept at 1 for all cases (stoichiometric fuel concentration). Additionally, the initial pressure was varied from 1.1 to 2 bar. Based on the hydrogen combustion reaction (1), and the methane combustion reaction (2):

$$2H_2 + O_2 \rightarrow 2H_2O \quad (1)$$

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \quad (2)$$

it is possible to calculate the volume of O_2 required to satisfy the stoichiometry of the reactions indicated above (3). If considering the hydrogen mole fraction of the mixture with X, it is:

$$V_{O_2} = \frac{X}{2} + 2 \cdot (1 - X) \quad (3)$$

and the corresponding air volume (4) is:

$$V_{air} = \frac{V_{O_2}}{0.20942} \quad (4)$$

For the sake of comparison, the properties of fuel-air mixtures have been calculated by using the CEA program [9].

3 Results and Discussion

Figure 2 shows the flame velocity as measured for hydrogen-methane mixtures, ranging from pure hydrogen to 30 $\%_v$ of methane, in the experimental tube described above. Three regimes can be observed in all curves. After the initial deflagration regime, the flame first accelerates to a sonic regime at the burned gas temperature. Then, for low content of methane, a dramatic increase of the flame velocity up to the detonation regime is observed. For pure hydrogen, a flame velocity of slightly above 2000 m/s is obtained, which is close to the C-J velocity at 1.1. bar if considering a closed tube test (hence an increasing pressure).

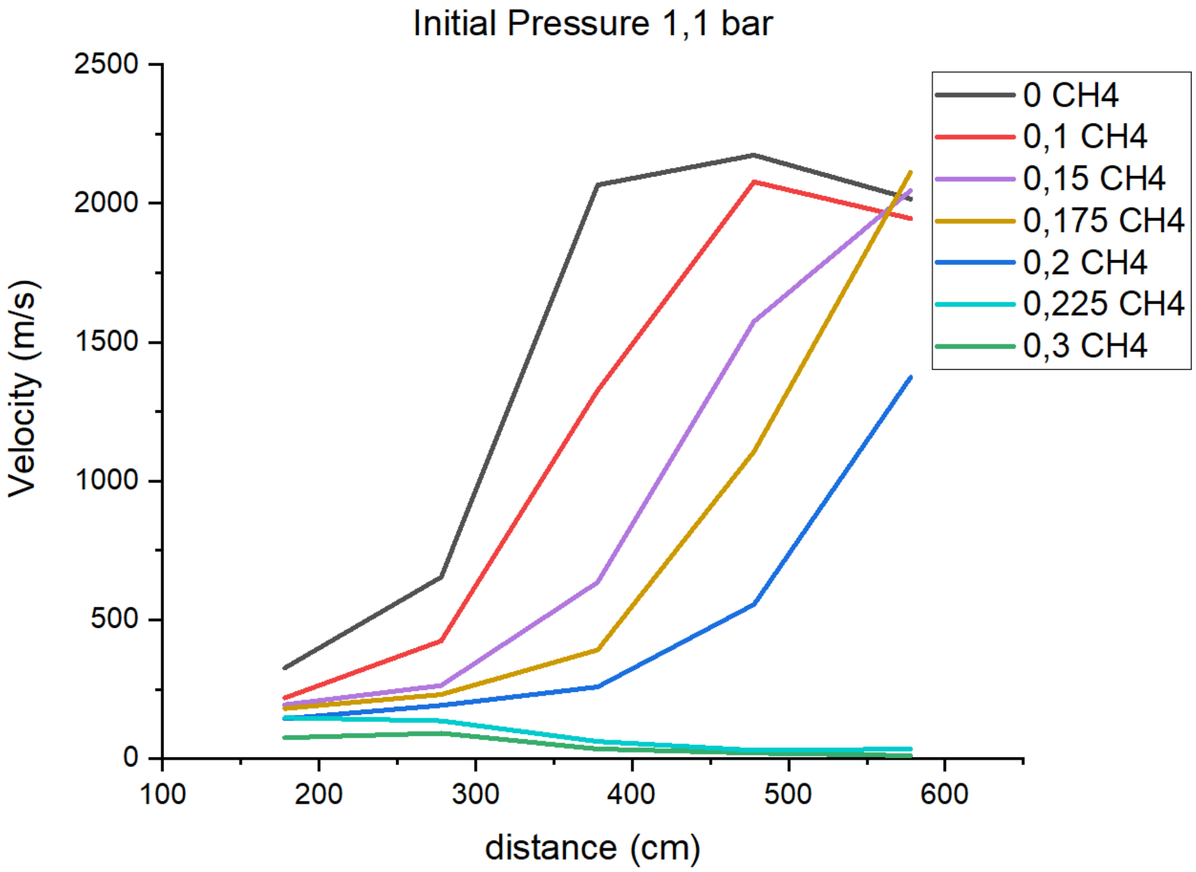

Figure 2: Influence of increasing the methane content on the position of the DDT.

As expected, the run-up distance increase with an increasing fraction of methane, in correspondence with the flame acceleration. When DDT is observed the C-J of about 2000 m/s is reached for all mixtures. These values correspond to the values given in the following table, which shows the characteristic properties of the methane-hydrogen mixtures analyzed in this work, if considering that the pressure has reached almost the adiabatic flame temperature (about 5 bar) due to pressurization(the tube is closed).

Table 1: Properties of the hydrogen-air mixtures analyzed in this work as calculated by CEA [9]. Initial pressure: 1.1 bar and 5 bar, at ambient temperature. Fuel at stoichiometric concentration (λ = 1).

CH_4, $\%_v$	H_2, %	Initial Pressure (bar)	Sonic velocity at the burned gas temperature (m/s)	C-J (m/s)	Pressure (bar)
0	100	1.1	1090.4	1966.8	17.17
10	90		1062.2	1916.1	17.62
20	80		1044.3	1884.2	17.93
30	70		1032.1	1862.4	18.17
0	100	5.0	1111.1	1995.8	79.85
10	90		1081.4	1942.8	81.80
20	80		1062.7	1909.8	83.20
30	70		1050.0	1887.2	84.26

It is quite important that, as seen in Figure 2, a tipping point above 20 % of methane in which the flame velocity is typically in the deflagration regime and no DDT is observed. To obtain robust results also on the possibility of the transition at the tipping points a total number of 116 tests were conducted so far varying the gas fractions and the initial pressure. The probability of a transition to a DDT is displayed in Figure 3.

It can be clearly seen that the increasing pressure results in a higher possibility of a DDT. For the above-mentioned fraction of 20% of methane, one of four tests showed a DDT while increasing it only slightly no test showed a sign of a DDT. Decreasing it slightly the possibility increases severely.

An estimation on which pressure-ratio-length combination of methane and hydrogen a DDT might occur, especially for the allowed amounts that are present in the moment in gas grids will be established and presented with further tests.

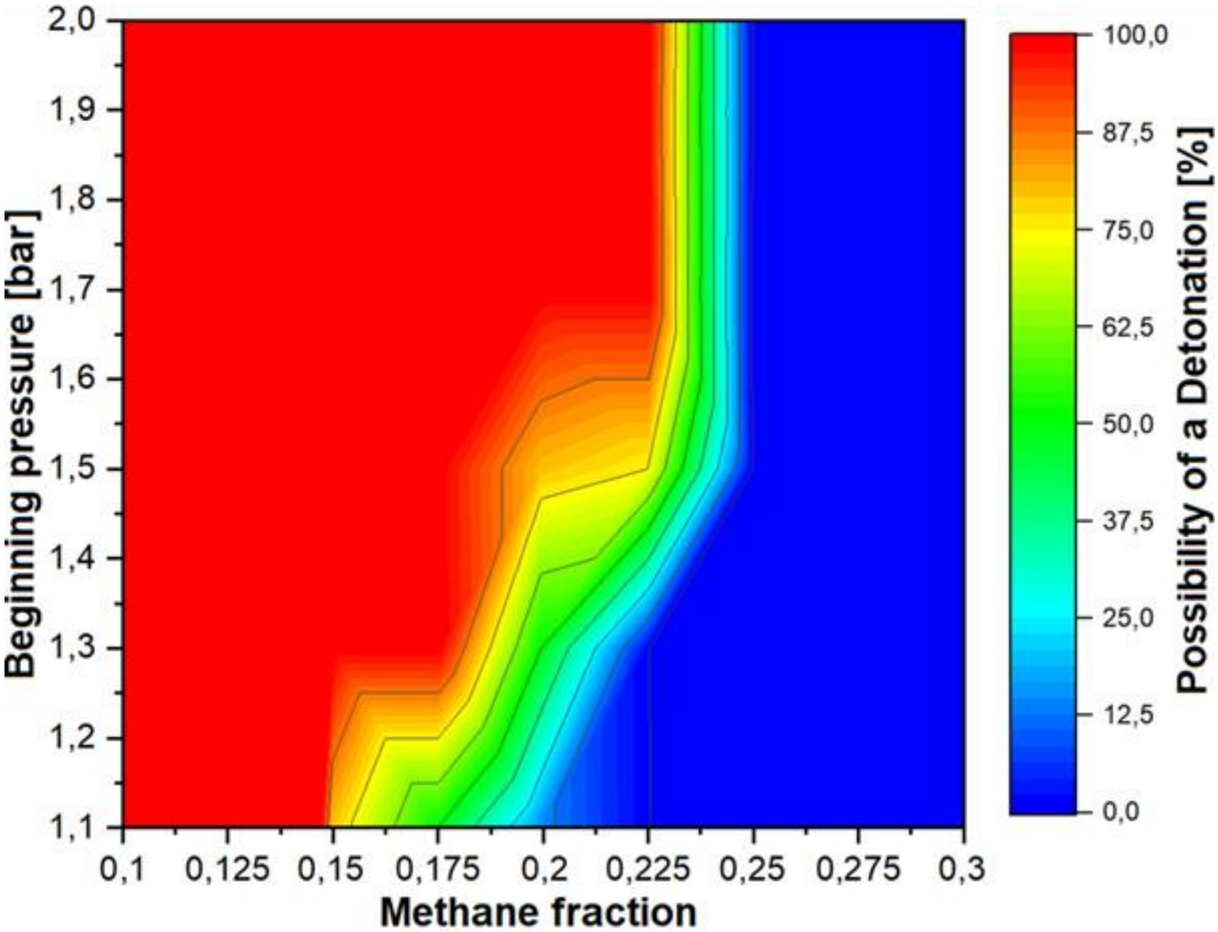

Figure 3: Influence of pressure on the possibility of the hydrogen-methane-air mixture to a DDT

4 Conclusions

The tests showed that an increase in pressure leads to a lower ratio of hydrogen/methane being able to detonate in smooth tubes, hence without obstacles. This first approach serves as the basis for further tests increasing the length and the diameter of the tube as well as the beginning pressure of methane-hydrogen-air mixtures to see when the allowed amount of 20 $\%_v$ of hydrogen, that is allowed presently, would lead to a detonation in case of an unintentional admixture of air.

References

[1] DVGW (2021). Wasserstoff-Beimischung - Sicherheit in Ihrem Zuhause. Online available under: https://www.dvgw.de/medien/dvgw/leistungen/publikationen/sicherheit-h2-beimischung-dvgw.pdf

[2] Volkmar Schröder, Enis Askar, Temir Tashqin (2016). Sicherheitstechnische Eigenschaften von Gemischen aus Wasserstoff und Erdgas. 14. Kolloquium zur chemischen und physikalischen Sicherheitstechnik.

[3] Askar E., Schröder V., Schütz S., Seemann A. (2016). Power-to-Gas: Safety Characteristics of Hydrogen/Natural- Gas Mixtures, Chemical Engineering Transactions, 48, 397-402.

[4] Salzano, E., Pio, G., Ricca, A., Palma, V., The effect of a hydrogen addition to the premixed flame structure of light alkanes (2018) Fuel, 234, 1064-1070.

[5] Salzano, E., Cammarota, F., Di Benedetto, A., Di Sarli, V., Explosion behavior of hydrogen-methane/air mixtures (2012) Journal of Loss Prevention in the Process Industries, 25 (3), 443-447.

[6] Lu-Qing Wang, Hong-Hao Ma, Zhao-Wu Shen, Dai-Guo Chen (2018). Experimental study of DDT in hydrogen-methane-air mixtures in a tube filled with square orifice plates. Process Safety and Environmental Protection. Volume 116, 228-234.

[7] I.O. Shamshin, M.V. Kazachenko, S.M. Frolov, V. Ya Basevich (2021), Deflagration-to-detonation transition in stochiometric mixtures of the binary methane-hydrogen fuel with air, Int. Journal of Hydrogen Energy, 46, 34046-34058.

[8] R. Porowski, A. Teodorczyk (2013). Experimental study on DDT for hydrogen-methane-air mixtures in tube with obstacles. Journal of Loss Prevention in the Process Industries. Volume 26, 374-379

[9] Chemical Equilibrium with Applications (CEA, available from the NASA Glenn Research Center at http://www.grc.nasa.gov/WWW/CEAWeb/).