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FLAME PROPAGATION IN GAS FEEDING PIPELINES TO THE IC ENGINE

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Abstract

Results from experimental investigation on flame propagation in a pipeline filled with gaseous combustible mixture consisted of hydrogen, methane or 20% hydrogen-methane is presented in the article. The mixture was prepared in separate cylinders and premixed before filling the pipeline. The tests were conducted under various relative equivalence ratio – lambda from 1.0 to 3.0 at pressure of 1 bar and temperature of 25°C. Hydrogen and methane were selected because these gases are main combustible fractions in several gaseous engine fuels (e.g. natural gas, syngas, biogas). Additionally, the mixture 20% hydrogen and methane, as potential engine fuel, was also under investigation. Flame front was detected with aid of IR photodetectors. Hence, the flame speed was resulted from distance divided by time. As observed, the flame propagation speed was over 100 m/s for both hydrogen and methane premixed mixtures. It was several times higher if compared with the laminar flame speed for these gases. It can be explained by additional acoustic effects (standing waves) taking place inside the pipeline. Results from this investigation can be useful in design and construction of the gas feeding system in the gas fuelled internal combustion engine.

Keywords: *flame propagation, laminar flame speed, methane, hydrogen, combustion*

1. Introduction

Investigation on flame propagation in various vessels have been of interests in several R&D institutions. Among others, well-known works by Teodorczyk [1], Pizutti [2], Kawakami [3, 4] and Thomas [5] dealing with hydrogen combustion in tubes as well as mechanisms from deflagration to detonation combustion, significantly extend knowledge in the field. As known, the specific parameter characterizing flame propagation for premixed combustible mixtures is laminar flame speed (LFS) which is determined in lab scale with aid of the Bunsen burner. The LFS is relatively low in comparison to real flame speed due to turbulent effect and additional phenomena associated with combustion of gases in real conditions. There are two combustion types depending on combustion rate influencing flame velocity as follows [11, 15]:

- deflagration,
- detonation.

Flame, depending on flowrate, can be distinguished into:

- laminar flame,
- turbulent flame.

Taking into account fuel-oxidizer zones someone can divide flames as follows:

- premixed flames,
- diffusion flames.

The laminar flame speed (LFS) is physicochemical property of the air-gas combustible mixture, and is defined as the speed at which a steady planar flame front propagates in a premixed, quiescent mixture in front of the flame in a direction normal to the plane. The LFS can be considered as the useful parameter in evaluating the fuel burning rate in the internal combustion engine (ICE), hence it can affect both performance and toxic exhaust emissions from the engine [12]. On a fundamental level, the flame speed is an important target for kinetic mechanism development and validation [1, 6, 7]. Knowledge of flame propagation close to a wall and flame – wall interactions are of interest due to investigating several phenomena dealing with flame propagation in tubes, misfiring events in the IC engine, optimization of combustion, and reduction in toxic exhaust emissions etc. etc. [1-3, 7-10, 13]. As observed, flame propagation can be easily transformed from deflagration to detonation regime while propagating in tubes [1, 5]. Several works on flames propagation through various obstacles in tubes were conducted by Kawakami et al [3, 4]. They concluded that real flame speed can be several times higher when propagating in tubes. The average flame speed with the swirl flow is remarkably increased as compared with the case of laminar flow.

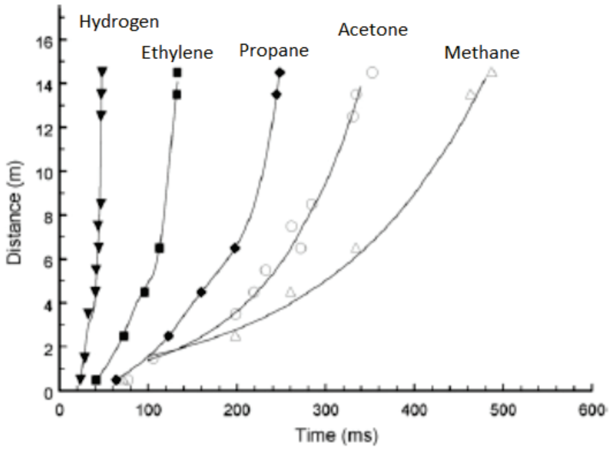

Fig. 1. Flame arrival time for selected fuel-air mixtures: hydrogen, ethylene, propane, acetone and methane [5]

As observed from Fig. 1, average velocities of flames can be easily determined, hence they are as follows: approximately of 150 m/s for hydrogen and 30 m/s for methane mixtures.

2. Test bed description

Investigation presented in this article was conducted at the test bed depicted in Fig. 2.

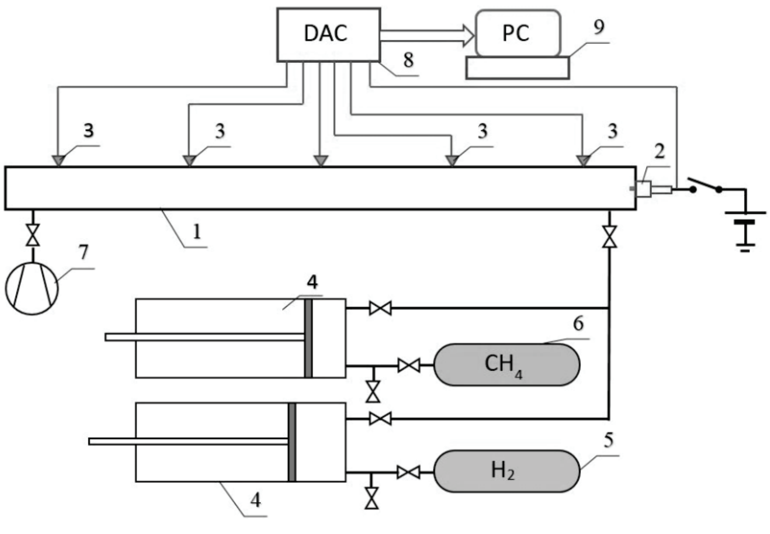

Fig. 2. Test bed: 1 – the research pipe, 2 – sparking plug, 3 – photodetectors, 4 – vessels for mixture preparation, 5 – H2 tank, 6 – CH4 tank, 7 – vacuum pump, 8 – A/D converters, 9 – data acquisition system

It consists of the research pipe with internal diameter of 25 mm and length of 1190 mm. Combustion initiation was realized by the spark plug with variable discharge energy. The pipe was 1-side-closed. Along the pipeline there are 5 IR detectors sensitive to radiation of 920 nm. They are located with distance from the spark plug as follows: 100 mm, 350 mm, 600 mm, 850 mm and 1100 mm. The second end of the pipe was plugged with an elastic paper plug preventing external air to flow into the pipe inside. While the pressure inside slightly increased above atmospheric level, the plug was immediately pushed out. Combustible mixture at required ratio by volume was formed in the two cylinders connected to each other. Appropriate amounts of gas and air were sucked into the cylinders and next were premixed by alternately pushing and pulling the cylinders several times. Total volume of these two cylinders were higher than volume of the pipe, thus, exceed amounts of the mixture were released to the environment before pugging the pipe. Prior to filling the pipe with the mixture, the air from pipe inside was sucked out by the vacuum pump.

Fuels applied for the research works are presented in Tab. 1.

Tab. 1. Fuels for the tests

No.	Fuel	Pressure	Temperature	λ
		hPa	ºC	–
1	H_2	995…998	24.5...25.0	1.0; 1.2; 1.5; 2.0; 3.0
2	CH_4	995…998	24.5...25.0	1.28; 1.6; 2.2; 3.05;
3	80% CH_4 + 20% H_2	995…998	24.5...25.0	1.2; 1.5; 1.9; 2.05; 2.9; 3.1

3. Measurement methodology

Voltage signals from the IR detectors and the spark discharge signal were recorded with sampling interval of 10 μs (sampling frequency of 100 kHz). The exemplary plot showing these signals is depicted in Fig. 3. Voltage signals from detectors were in line with IR radiation intensity generated by the flame passing the detectors. The problem with the flames signals was how to detect the flame location in it. The following two methods were proposed and verified:
– flame location at 50% normalized voltage signal (Fig. 4),
– flame location at peak of the first derivative from the voltage signal (Fig. 5).

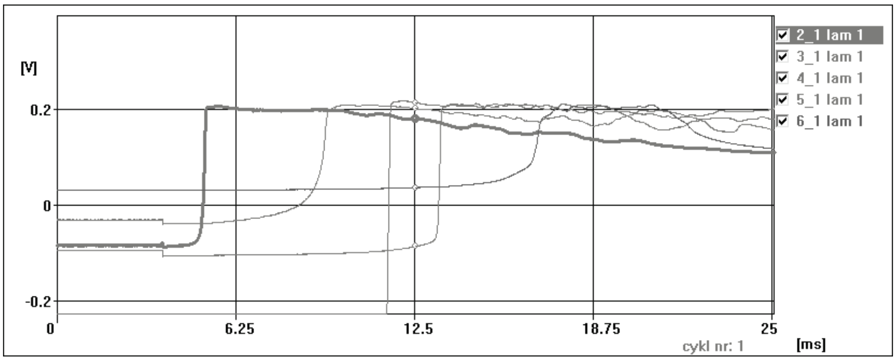

Fig. 3. Exemplary voltage signals from IR detectors

On the basis of these peaks locations at each point on the pipeline, mean flame speeds were determined with the equation (1).

4. Results and discussion

Figure 6 shows the average flame's propagation velocity in the subsequent sections of the pipe for three mixtures of hydrogen, methane and hydrogen-methane with air for the relative equivalence air-fuel ratio λ of 1.3. There is a visible effect of the impoverishment of combustible mixtures on decreasing flame propagation velocity. As depicted in Fig. 6 the flame propagation speed is remarkably higher with respect to LFS for each combustible mixture. In case of air-hydrogen mixtures with lambda from the range λ = 1…1.5 the maximal flame speed reaches 20-160 m/s, as depicted in Fig. 7. For leaner air-H_2 mixtures it significantly drops to 6…40 m/s, while the LFS measured in lab scale does not excess 5 m/s. Similar correlations are observed in tests with air-CH_4 mixtures (Fig. 8). For the mixture with λ = 1.3 the maximal flame speed is reaches 100 m/s. For tests with λ = 2.2…3.1 measured speed is lower in between 5.8-15.4 m/s. However, as known the LFS for stoichiometric air-CH_4 premixed mixture is around 0.4 m/s.

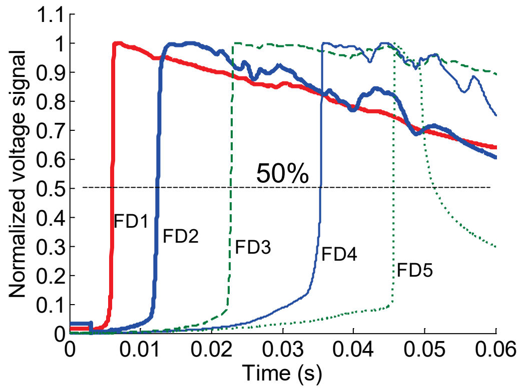

Fig. 4. Normalized voltage signal from 5 detectors for hydrogen combustion

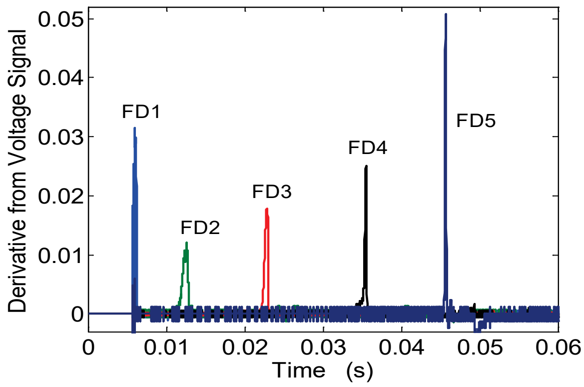

Fig. 5. Derivative from voltage signals for hydrogen combustion

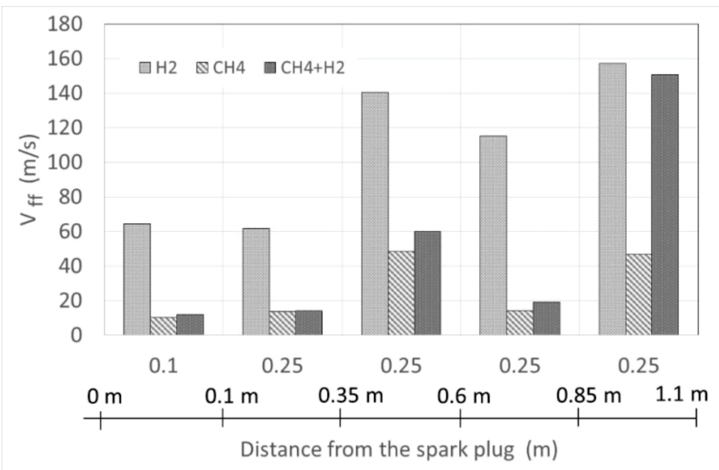

Fig. 6. Exemplary front flame propagation speed for three fuels along the pipeline at relative equivalence ratio lambda = 1.2

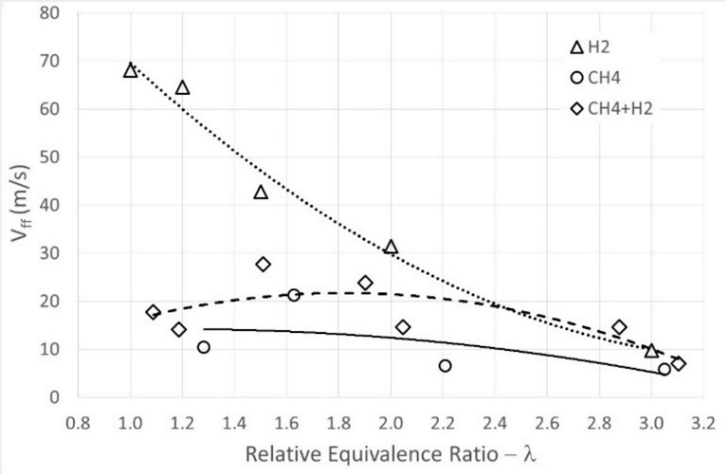

Fig. 7. Average flame speed V_{ff} vs. lambda for 3 fuels H2, CH4 and CH4+H2 at the 0-1 first segment of the pipeline

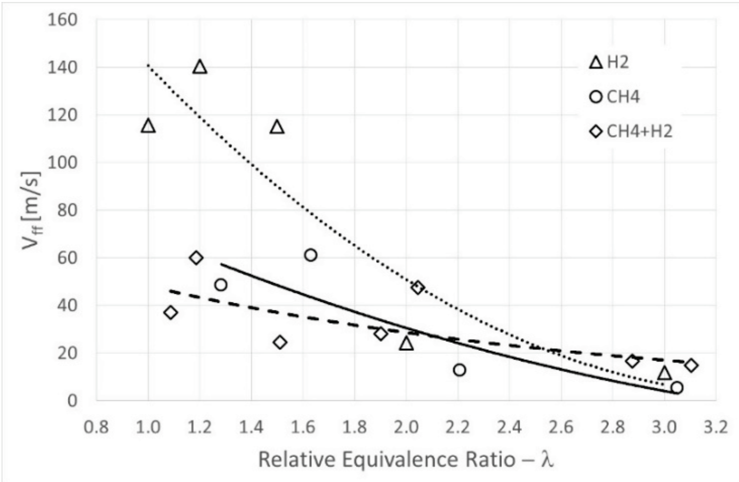

Fig. 8. Average flame speed V_{ff} vs. lambda for 3 fuels H2, CH4 and CH4+H2 at the 2-3 segment of the pipeline

Obtained results clearly indicate that the flame propagation in the tested pipeline is not laminar in nature. A common feature of most results is the increasing propagation speed of the flame in the initial section of the pipe. The maximum flame velocity was observed in the case of richer hydrogen mixtures. It occurred at a distance of 0.6-0.8 m from the ignition point and for methane mixtures at the distance of 0.6 meter from the ignition point. For leaner mixtures, no clear maximum flame velocity was observed - a common feature is its low increase in the final section of the pipe. This increase also occurs with richer methane blends. However, for richer hydrogen mixtures, the flame's propagation speed decreases in the final section of the pipe. The following conclusion arises from these observations. For the mixtures near to stoichiometric air-fuel ratio there is a clear acceleration of the flame in the initial section, then in the second part of the tube the velocity decreases. It has been confirmed in several experiments. The highest flame's front velocity rises to 160 m/s, which may indicate combustion similar to detonation. Such a high flame speed was noticeable for fuels containing hydrogen, i.e. pure H2 and a mixture of 20% H2 with CH4 [14]. For leaner mixtures, combustion becomes deflagration. The CH4 flame behaves similarly, there was no excessive increase in speed along the length of the pipe.

5. Error analysis

Mean flame speed in the pipe sections can be calculated with the equation:

$$V_{ff} = \frac{S_i}{t_{i+1} - t_i} = \frac{S_i}{\Delta T_i}, \tag{1}$$

where:
V_{ff} – mean flame speed,
S_i – length of the i - section,
t_{i+1} – time when the voltage signal from the photodetector i + 1 achieves its 50%,
t_i – time when the voltage signal from the photodetector i achieves its 50%.

Hence, the relative error for this flame speed V_{ff} can be determined as follows:

$$\frac{\Delta V_{ff}}{V_{ff}} = \left|\frac{\Delta S_i}{S_i}\right| + \left|\frac{\Delta T_i}{T_i}\right|, \tag{2}$$

where:
$\Delta T_i = 20$ µs, $\Delta S_i = 1$ mm – absolute errors in time and distance measurements.

Relative error calculated within this method was in between 1.1 and 2.4% for the first shortest section of the pipe of 0.1 m. In further longer sections (0.25 m) this error was in the range from 0.44 and 1.7%.

Next task was to determine a relative error in "lambda" determination. Temperature of the gases (air, methane and hydrogen) did not differ significantly from each other, hence one can assume, that mass ratio can be replaced by volume ratio of the specific gases. The method was the same, based on determining the exact differential from the equation (3):

$$\lambda = \frac{V_a}{(A/F)_s \cdot V_g}, \tag{3}$$

where:
V_a – air volume,
V_g – gas volume (H_2, CH_4),
$(A/F)_s$ – air-to-fuel stoichiometric ratio by volume.

The relative error for lambda can be determined with the equation (4):

$$\frac{\Delta\lambda}{\lambda} = \left|\frac{\Delta V_a}{V_a}\right| + \left|\frac{\Delta V_g}{V_g}\right|, \tag{4}$$

where:
$\Delta V_a = 5$ cm^3 – absolute error in measuring air volume,
$\Delta V_g = 1$ cm^3 – absolute error in measuring gas volume.

The lambda relative error for air-hydrogen mixture determined with this equation was in the range from 2.1% to 2.6%, for air-methane mixture was between 3.4-5.9%. The largest relative error was for hydrogen-methane-air mixture. It was between 7.3-13% depending on how the mixture was lean. The largest error was determined for the leanest mixtures in all cases.

Summing up, the results are charged with relative errors which can be accepted in the investigation. As determined, these errors do not remarkably affect final results for V_{ff}.

6. Conclusions

Three gases: hydrogen, methane and mixture of methane and 20% hydrogen were tested with respect to flame propagation resulting from their potential ignition in the pipeline. There are conclusions from the investigation as follows:

– real flame propagation speed for the investigated gases is several times higher than the laminar flame speed determined in laboratory conditions for pure laminar flows,

- hydrogen flame propagates faster than methane one; methane flame is faster than flame from premixed 20% hydrogen and methane,
- flame propagation speed decreases significantly with increase of excess air expressed by relative equivalence ratio lambda,
- it was observed in all these cases, that flame speed is not constant. Moreover, it is in neither growing nor falling trend. As observed, the flame accelerates, hence the flame speed increases at the first half of the pipe and next it goes down in the second section of the pipe. It might be caused by acoustic effects coming from sound waves generated by accelerated flames propagation, which reflect from the closed end of the pipe and might provide intensive turbulence to the flame zone. This effect needs further investigation.

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