Experimental and Computational Study on DDT for Hydrogen-Methane-Air Mixtures in Tube with Obstacles

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Introduction

Considering the research works on DDT in obstructed tubes, it should be noted that the first fundamental study was conducted by Chapman and Wheeler [1] who placed an orifice plates in a smooth walled tube in order to promote flame acceleration. In their research the maximum flame velocity in the 5 cm inner diameter tube without obstacles for methane-air mixtures was about 10 m/s. But the same tube with orifice plates gave a maximum flame velocity over 400 m/s. Unfortunately, during this experimental research a transition moment was not observed, due to limited diameter of the tube. In the few next decades a lot of experimental investigations were performed to see how the DDT occurs in obstructed channels. Significant work was done in this area by Shchelkin [2, 3], Teodorczyk et al. [4], Shepherd [5] and others. Shchelkin [3] proposed that flame acceleration was governed by turbulent fluctuations in the unburned gas ahead of the flame that led to an increase in flame area. Since the unburned gas velocity is related to flame velocity there is a feedback loop between the flame velocity and flame area that results in efficient flame acceleration. Depending on the fuel concentration and initial and geometrical conditions, steady flame propagation in obstructed tube progresses in a one of following regimes [6]:

- flame quenching - flame fails to propagate,
- subsonic low-velocity flame - flame propagates at a speed much lower than the speed of sound in the combustion products,
- CJ deflagration - high-speed flame propagating with the velocity close to the speed of sound in the combustion products (600 - 1200 m/s),
- quasi-detonation - flame propagates with the velocity between the speed of sound in the combustion products and the CJ value,
- DDT and detonation - flame velocity is close to CJ value.

The aim of this study is to investigate both experimentally as well as computationally the phenomeon of DDT in binary gaseous fuels with air using a long tube with different obstacles configuration.

Experimental set-up

To investigate the deflagration-to-detonation transition for stoichiometric hydrogen-methane-air mixtures, an experimental study was first performed in 6 m long circular cross section tube with inner diameter D = 140 mm. All tested mixtures were stoichiometric hydrogen-methane-air mixtures with different methane contents and with initial conditions of 1 atm and 293 K. The wave propagation was monitored by piezoelectric pressure transducers PCB. Pressure transducers were located at different positions along the channel to collect data concerning DDT and detonation development. Experimental apparatus is shown in Figure 1. Tested mixtures were ignited by a weak electric spark at one end of the tube. Gas mixtures were produced using the partial pressure method and mixed by in a cylinder. After sufficient time the gas mixture was introduced to the experimental tube, to the desired pressure.

Figure 1: Some pictures of experimental facility

Experimental tube consisted of four sections (2 x 2 m and 2 x 1 m) jointed together and equipped with different configurations of obstacles inside. Configurations of obstacles were used with BR from 0.4 to 0.7. Internal diameters of particular obstacles were chosen between 77 mm up to 108 mm and numbers of obstacles varied from 12 to 35. Obstacles inside the tube were located at various distances S which were equal to 1 x D = 140 mm, 2 x D = 280 mm and 3 x D = 420 mm.

Results and discussion

For the smooth channel without obstacles only turbulent deflagration regime was achieved with the velocity of about 500 m/s. Four values of blockage ratio BR were studied: 0.4, 0.5, 0.6 and 0.7. Figures 2 shows the example of average wave velocity along the tube for all tested hydrogen-methane-air mixtures for the largest distance between obstacles S=420 mm and BR equal to 0.6. For BR = 0.7 DDT was observed only in hydrogen-air mixtures while for hydrogen-methane-air mixtures only CJ deflagration and quasi-detonation regimes were recorded. Adding methane to mixture DDT was observed for blockage ratio from 0.4 to 0.6, mostly for distances between obstacles equal to 280 mm and 420 mm.

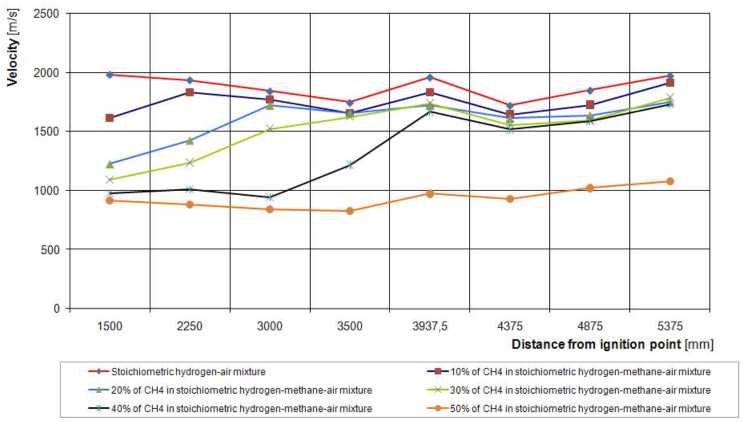

Figure 2: Average wave velocities of stoichiometric hydrogen-methane-air mixtures for BR = 0.6 and S = 420 mm.

In case of low blockage ratio of 0.4 and distance between obstacles S=420 mm we noticed a DDT for mixtures up to 50 percent of CH_4 contents in the mixtures. For this case the 3D spacing was the optimum in obstacle densities. Higher obstacle densities, like in 1D spacing, resulted in quasi-detonation regime for mixtures containing from 30 percent up to 50 percent of CH_4, with velocities of 1500 m/s. With denser obstacles configuration the velocity of fast deflagration was lower due to larger momentum losses. At medium blockage ratio (BR=0.5) the obstacle spacing for the detonation hazard was closer to S=3D. At 2D spacing transition to detonation was noticed for mixtures containing up to 30 percent of CH_4. Other mixtures achieved quasi-detonation regime. At 1D spacing DDT for mixtures containing up to 20 percent of CH_4 was recorded. At blockage ratio (BR=0.6) detonation occurred only for mixtures containing up to 10 percent of CH_4 for S = 3D. Other mixtures achieved quasi-detonation and CJ deflagration regimes.

We also performed CFD simulations for the same conditions of hydrogen-methane-air mixtures and the geometry of the tube. The simulation tool used in this study is a centered TVD-method solver with a combustion model combining two-step kinetics and turbulent burning velocity method. To model the combustion processes three species are conserved; reactants, radicals and products. To reduce the number of control volumes axis-symmetric cylindrical coordinates are assumed. This assumes that there is no flow or waves traveling in the tangential direction and the computational domain is two-dimensional. The control volumes are constant quadratic 0.5 mm length. The turbulence is handled by a one-equation turbulence model for the turbulent kinetic energy. As an example, Figures 3 shows some pressure and temperature distributions obtained from our simulations. This case presents a quasi-detonation state of 30 percent of CH_4 in the mixture, obtained between 2.25 and 4 m from the ignition along the tube.

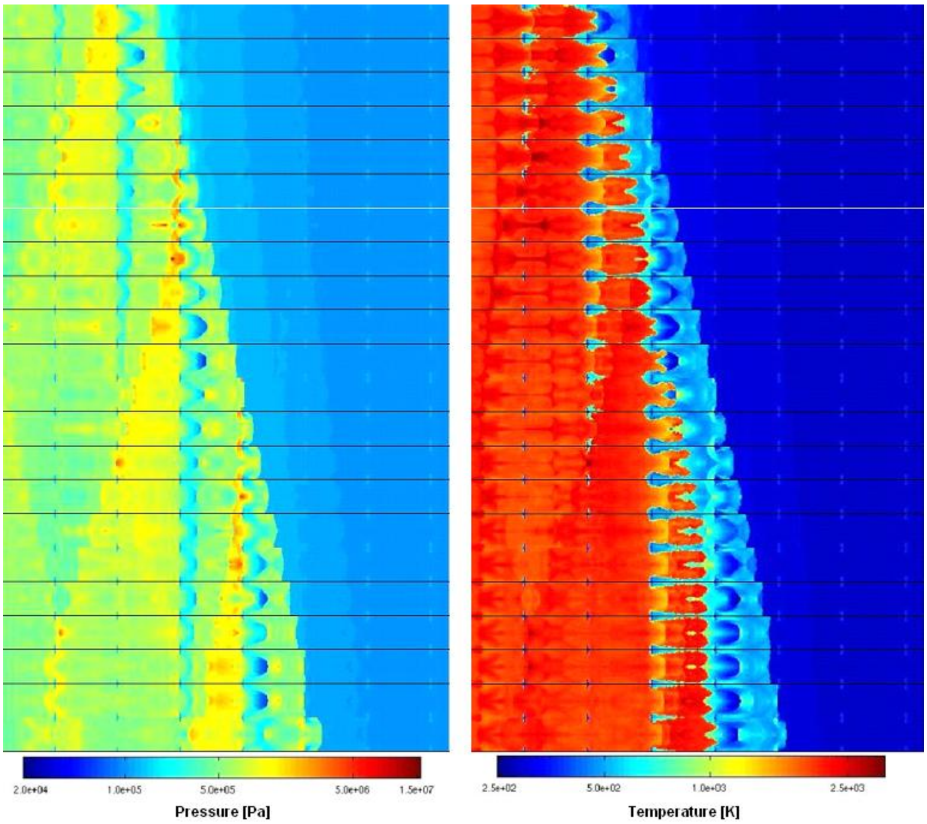

Figure 3: Pressure and temperature distribution along the tube (between 2.25 and 4 m from the ignition) for the DDT simulation. Case including: 30 percent of CH_4 in the mixture, BR = 0.5, distance between obstacles 280 mm.

We also did some numerical calculations of the flame speed for each hydrogen-methane-mixtures. Some of them are shown on Figure 4 with BR=0.6, S=3D and BR=0.5, S=2D all for 20 percent of CH_4 in the mixture. For these cases we also noticed a confirmation with our experimental results for wave velocity and pressure profiles.

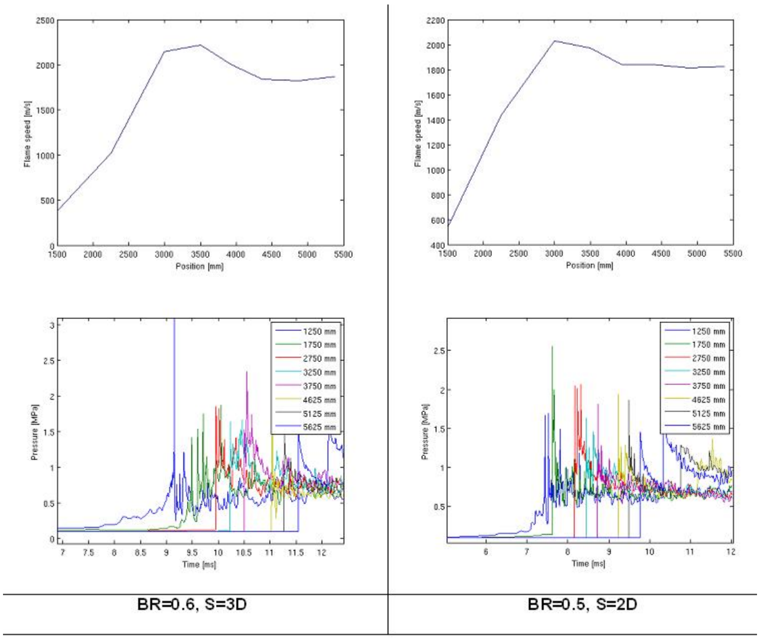

Figure 4: Flame speed and pressure profiles from DDT simulations: 20 percent of CH_4 in the mixture, BR=0.6 with S=3D and BR=0.5 with S=2D.

References

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