INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2016) 1–10

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Small-scale flame acceleration and application of medium and large-scale flame speed correlations

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ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form
6 October 2016
Accepted 7 October 2016
Available online xxx

Keywords:
Flame acceleration
Deflagration
Congestion
Hydrogen

ABSTRACT

The flame acceleration plays a major role on the explosion effects. Then, it is of importance to understand the flame acceleration process and to predict explosion effects in open and congested areas for industrial safety reasons. In this aim, small-scale deflagration experiments were performed in cylindrical congested volumes of hydrogen – air mixtures varying from 1.77 L to 7.07 L. The influence of the reactivity was studied since the equivalence ratio of hydrogen – air mixtures were ranging from 0.5 to 2. The congestion was realized with varying numbers of grid layers and configurations. Experimental results, in term of flame speeds, were compared to results from correlations of the literature. Correlations were also adapted to the small-scale and modified to take into account the volume and the reactivity of the combustible mixtures.

Introduction

It is well known that the overpressure generated during a deflagration process increases with the flame velocity [1,2]. When the deflagration occurs in a congested area, the obstruction in the path of the flame propagation can accelerate the flame due to the turbulence generated [3]. That is to say that the overpressure resulting of the deflagration can be greater in an obstructed area as compared to a free field. Numbers of experiments were achieved in order to better understand the process of flame acceleration and to predict this effect in an industrial context.

Several experiments were performed in obstructed tubes to analyze the mechanism of acceleration. For example, with methane-air mixtures in a 7 meters long and 0.3 m × 0.3 m square cross-section tube [4], in a 3.66 m long and 0.076 m × 0.076 m square channel [5] or more recently in a 4.25 m long and 0.162 m internal diameter [6,7] where the effect of obstacle separation distance and blockage ratio BR (20%, 30% and 40%) on methane-air (10% by vol.) mixture were studied. Boeck et al. [8] have studied the flame propagation with a single obstacle (50% BR) in a 0.4953 m long square channel (0.0762 × 0.0762 m^2) with a stoichiometric H_2/O_2 mixture. Flame acceleration of hydrocarbon-air and more specifically hydrogen-air mixtures were studied in three 11 m long tubes with 0.05, 0.15 and 0.30 m cross-sectional diameters [9], in an 11 m long tube and 0.05 m cross-sectional diameter [10] for example. Beauvais et al. [11] have discussed about the parameters influencing turbulent flame acceleration process, using experiments carried out with hydrogen-air mixtures (from 10% to 26% by vol.) in a 6 m long tube and 0.066 m internal diameter with 32% and 69% BR. Cross et al. [12] have studied DDT and the detonation propagation limits of hydrogen-air (17%–60% by volume) in a 6.1 m long, 0.1 m diameter tube filled with obstacles (44% BR)

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http://dx.doi.org/10.1016/j.ijhydene.2016.10.042

at atmospheric pressure. Indeed, hydrogen is of interest since it is widely used in the chemical industry, the fertilizer industry, the sector of petrochemical for example and it is in the containments of nuclear reactors in case of incident. Moreover, it is seen as an important energy carrier for the future. For example, experiments were performed in semi-confined layers with hydrogen-air mixtures, in a 2.5 m long rectangular channel with varying width of 0.3, 0.6 and 0.9 m [13]. Experiments at medium and large-scale involving hydrogen have been also undertaken. For example, Grune et al. [14] have studied the effect of obstacles in a cubical volume of 0.166 m^3 filled with a stoichiometric H_2 − air mixture. At large-scale, Sherman et al. [15] carried out experiments for nuclear reactor safety with H_2 - air mixtures (from 12% vol. to 30% vol. H_2 in air) in 30.5 m long rectangular obstructed channel and 1.83 m × 2.44 m cross-section (136 m^3). Dorofeev et al. [16] have studied the flame acceleration with lean hydrogen - air mixtures (from 9.8% vol. to 14% vol. H_2 in air) in a channel of 34.6 × 2.3 × 2.5 m coupled with a "canyon" of 10.55 m × 6.3 m × 2.5 m and a last channel of 24.75 m × 2.3 m × 2.5 m (total volume of 430 m^3). Royle et al. [17] performed experiments with several hydrogen concentration (0% vol. to 100% vol.) in methane-air mixtures in a 3 m × 3 m × 2 m congested volume (18 m^3). Groethe et al. [18] have realized experiments with mixtures composed of 15% vol. to 30% vol. H_2 in air inside a hemispherical volume of 300 m^3 filled with obstacles. Lowesmith et al. [19] have studied the flame acceleration of methane − hydrogen − air mixtures in a 26.2 m × 2.8 m × 3 m volume (220 m^3) using rows of obstacles.

In order to improve industrial safety, methods were developed from experimental results to predict explosion effects due to the flame acceleration in congested areas. Among them, two different types of methods can be distinguished: methods based on blast curves like the TNO multi-energy method [20] and the Baker-Strehlow-Tang method [21] or analytical method like models proposed by Grune et al. [14] or Dorofeev [22]. Indeed, Grune et al. [14] have developed a method from medium-scale experiments with a stoichiometric hydrogen-air mixture. The method proposed by Dorofeev [22] was based on medium and large-scale experiments (hydrocarbon-air mixtures and hydrogen-air mixtures).

To our knowledge, no papers deals with the flame acceleration in an open and congested area at small-scale with volumes inferior to 0.01 m^3. Then, in order to add data for the prediction of explosion effects, this paper will first present the experimental results for small-scale deflagrations in obstructed areas. The influence of the obstruction on the flame speed and the maximal overpressure was investigated with hydrogen − air mixtures in initial cylindrical volumes varying from 1.77 L to 7.07 L. Lean and rich mixtures were studied, since the equivalence ratios were ranging from $\Phi = 0.5$ to $\Phi = 2$. The second section of this paper will concern the application of the model of Grune et al. [14] and the model of Dorofeev [22] our small-scale experiments. Experimental results and predicted results in terms of flame speeds will be compared. Finally, the last part will present some models adaptations to take into account the volume, the geometry of the initial confinement and the reactivity of the mixtures.

Experimental setup

Experiments were performed on a 2.85 m long and 1.32 m width workbench (Fig. 1). An obstructed cylindrical volume, called flame acceleration device, was placed on the workbench.

It consisted in a cylinder made with n layers stainless steel grids with a diameter of 0.5 mm. Each grids were made of $2 \cdot \delta_m = 6$ mm square cells, with δ_m the half of the grid cell size. Consequently, the area blockage ratio of the obstacle, which is defined as the ratio of area blocked by obstacles to the cross-sectional area, was about 16%. Two heights h_0 (0.1 m and 0.2 m) and five diameters d_0 (0.125 m, 0.150 m, 0.175 m, 0.200 m and 0.300 m) were tested. The volume blockage ratio VBR and the pitch value Δ are reported in Table 1 for each configuration. The volume blockage ratio is defined as the ratio of the obstacles volume to the total volume of the obstructed zone, and the pitch is the distance between each layer.

The acceleration flame device was initially covered by a thin polyethylene film to contain a hydrogen-air mixture. This gaseous mixture was realized and regulated by two mass flow controllers. The mixture was injected at the center of the acceleration flame device during a sufficient time to flush the initial air through the gas outlet located on the top of the circular side of the structure. The ignition was made at the center of the device by a spark generated between two 5 cm long electrodes.

The nominal energy delivered was fixed to 350 mJ. Two kinds of pressure sensors were used, piezoelectric PCB transducers and B&K microphones. Seven piezoelectric transducers were located from 0.17 m; 0.22 m; 0.27 m; 0.32 m; 0.42 m; 0.52 m; 0.70 m to the ignition source. Four microphones were used in far field from 1.03 m; 1.23 m; 1.43 m; 1.63 m to the ignition source, due to their low measure range coupled with their high precision.

The flame front was followed with the help of a high speed video camera Phantom V7.3, recording at 70,000 frames per second. The flame velocity was determined with a homemade Matlab program applied on the treated video frames. The flame radius retained for the flame velocity calculation is a mean value of nine radii measured in an angular range of 10° to the horizontal at a high of 5 cm from the workbench. Indeed, the flame propagation distance and the flame velocity are greater for the horizontal direction than for other directions. A side view of the flame can be seen in Fig. 2 where the flame propagation was only interacting with one wall which is the surface of the workbench (boundary located at the bottom of the flame in Fig. 2). The maximal flame speed was determined at the outlet of the acceleration device due to the obstruction which hides the flame inside it.

Experimental results

Varying obstacles number at a fixed equivalence ratio

All tests were conducted with an equivalence ratio $\Phi = 1$ for all configurations reported in Table 1. A general trend (Fig. 3) shows that the maximal flame speed increases with the

Please cite this article in press as: Rocourt X, et al., Small-scale flame acceleration and application of medium and large-scale flame speed correlations, International Journal of Hydrogen Energy (2016), http://dx.doi.org/10.1016/j.ijhydene.2016.10.042