Research paper

Experimental and numerical investigation of the effect of end venting on flame acceleration in an obstructed channel

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Received : December 16, 2010 Accepted : March 24, 2011

Summary

Hydrogen-air deflagrations with venting at the end of obstructed tubes are studied experimentally and numerically. Mixtures with 13% vol. of hydrogen were ignited from the open end of the tube at the interface between fuel and the ambient air. Three venting ratios were selected, closed, 40% and 100%. In the presence of the venting, the flame initially propagates without acceleration at a velocity close to the laminar flame speed. After an induction period, of the order of1 sec, the flame accelerates more than 100 times, within a period of 3-30 ms, until the steady-state *choked* regime will be established. The mechanism conducing to such a rapid acceleration was numerically investigated.

Keywords : turbulent flames, venting, flame acceleration, explosions.

1. Introduction

Premixed deflagration experiments in tubes are usually initiated by a weak source of energy, like a spark, which produces the ignition of the reactive mixture in one of the extremes of the channel. The flame starts to propagate slowly but, due to the existence of obstacles in a confined space, it suffers strong accelerations. The expansion of the burned gases generates turbulence that in a feedback mechanism increases the effective burning rate causing a faster expansion. This virtuous loop may be countered, or even interrupted, by flame quenching or by lateral or end venting. Dorofeev et al.1), 2) and Kuznetsov et al.3) have developed some criteria to predict the flame propagation regime in obstructed channels. As a result, three main propagation categories, *slow* sub-sonic, *fast* sonic (choked) and *quasi-detonations* were identified for such configurations.

Ciccarelli et al.4) and Alekseev et al.5) found in their research that *Fast* and *quasi-detonations* explosions may be suppressed by the use of venting orifices. Furthermore, they confirmed that the amount of reactive mixture necessary for the development of sonic flames or DDT grows with an enlargement of the venting surface. Alexiou et al.6) found additionally that an end opening reduces the combustion pressure with a higher efficiency than lateral one.

Flames propagating in obstructed channels ignited from its open end were investigated in this paper. In such configuration, a prolonged *quasi-laminar* propagation phase is followed by a sudden and extremely violent flame acceleration which culminates in the *sonic* regime. In order to get a sound understanding of the phenomenon, the authors have carried out the experimental and numerical analysis presented here.

2. Description of the experiments

The experiments were performed in the DRIVER facility Scholtyssek7), which is an obstructed combustion tube with a total length of 12.2 m and an internal diameter of 174 mm, (see Fig. 1). The degree of obstruction selected

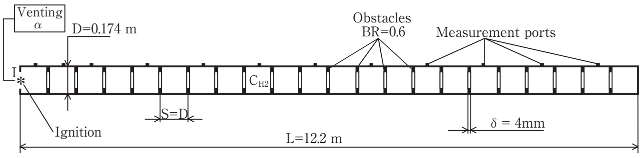

Fig. 1 Combustion tube configuration

was equal to 0.6. A 13% vol. hydrogen-air mixture at ambient conditions was ignited at the open end, directly at the interface between the inflammable mixture and the surrounding air. The instrumentation included photo diodes and pressure gauges installed along the channel. The venting ratio α of the orifice was varied from 0% (fully closed) up to 100% (fully open).

In Fig. 2 the experimental results of the flame propagation for closed (left) and vented channel (right) are shown. In those distance-time (x-t) diagrams, the pressure and light records are plotted against time in vertical direction. In the closed channel (left), the flame accelerates immediately after reaching the first obstacle, steepens into a shock wave and finally reaches the *choked* regime.

In the presence of venting, the flame propagates initially in a *quasi-laminar* regime and produces no significant pressure increments or relevant flow motion, or turbulence, ahead the flame. Around1s after the ignition, the flame suddenly accelerates from the *quasi-laminar* to an stable *choked* regime within an interval of 20-30 ms. It was experimentally confirmed that even a fully open end cannot prevent flame acceleration to the sonic regime.

3. Numerical simulation

In order to analyze the mechanism of the flame acceleration in presence of end discharge, three simulations with venting ratios 0%, 40% and 100% were carried out. The calculations were performed with the standard k-ε turbulence modelwith initial levels of turbulence and dissipation of 10^{-4} m^2/s^2 and m^2/s^3, Arntzen[8], respectively. The combustion was modeled with the *KYLCOM* model, Yanez[9], coupled with the turbulent burning velocity correlation due to Schmidt[10]. *KYLCOM* model does not take into account the effects of flame wrinkling due to flame instabilities. Particularly for this problem, neglecting the ***thermo-diffusive*** instability will cause an under prediction of the flame velocity until the flame acceleration takes place, Kuznetsov et al.[11], as we will see later. To reproduce the products release into unconfined ambient air, a supplementary numerical domain with *non reflective* boundary conditions was added to beyond the vent area. The performance of the calculation was improved simulating only one quarter of the transversal section of the tube.

4. Results and analysis

The Figure 3 displays a comparison of the flame propagation obtained from the results of simulations and experiments. The *closed* case shows the typical and characteristic fast acceleration pattern. For the cases with venting, the simulations correctly predict the existence of two regions with different propagation regimes. In spite of the qualitative agreement, in the *quasi-laminar* propagation phase the velocity of the flame was much faster in the experiments than in the calculations. Two non

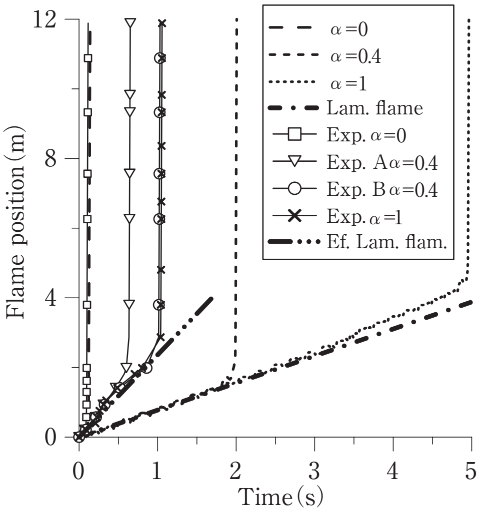

Fig. 3 Flame position. Dashed lines, calculations. Thin continuous lines with symbols, experiments. Thick lines, laminar and quasi laminar regime propagation. Venting ratio is indicated in the legend.

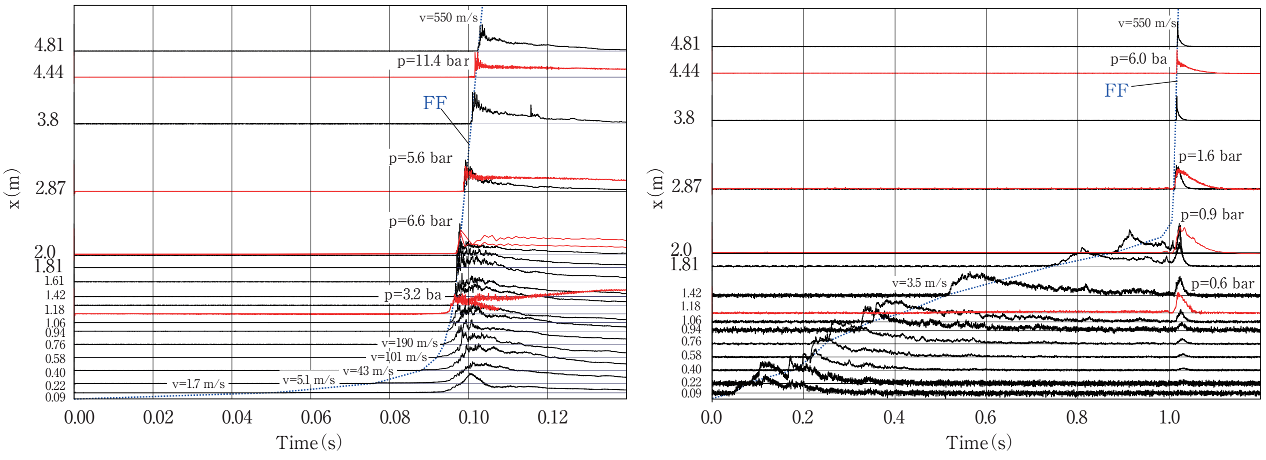

Fig. 2 x-t−Diagram of the initial flame propagation in closed (left) and 40%-vented (right) obstructed channels : flame front (FF) trajectory (blue dots) ; light signals (black lines) ; pressure records (red lines). Pressure peaks and local visible flame velocities are shown at the plot.

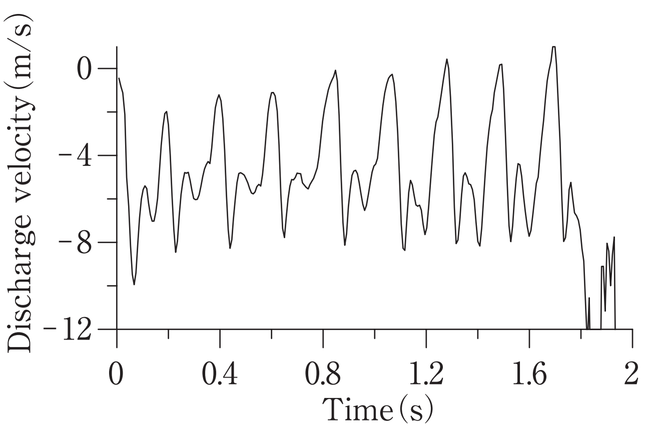

Fig. 4 Calculated discharge velocity in venting orifice for the case α=0.4.

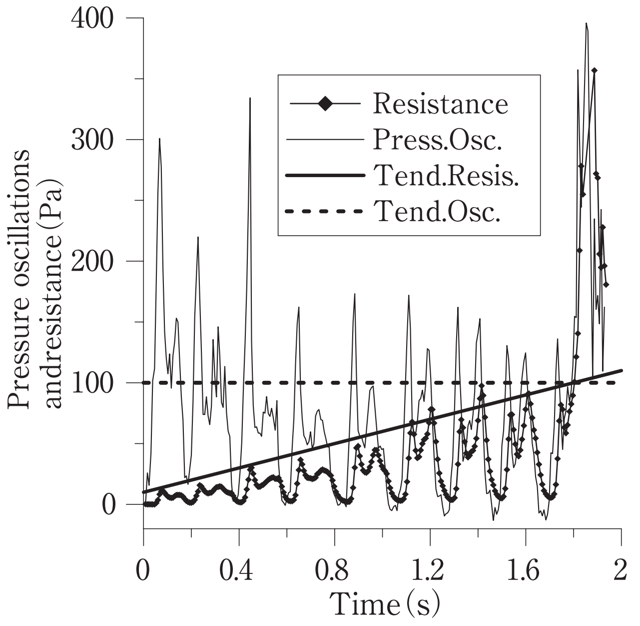

Fig. 5 Calculated pressure oscillations and resistance obtained for the case α=0.4.

modelled processes are responsible of this. The already mentioned ***thermo-diffusive*** instability and the positive Markstein number which tends to decrease the local burning velocity when positive flame stretch appears. In the opinion of the authors, those combined effects account for the divergences obtained between the measured and the calculated flame propagation speed (dashed-dotted thick lines) and represent a factor three enhancement. The line applying to the experiment was calculated obtaining the slope of the propagation in the quasi-laminar regime while the slope of the line applying to the calculations was obtained from the experiments of Dowdy[12] et al.. The test with 40% of venting was carried out twice, and a significant delay, from ~ 0.6 s to ~1s in the flame acceleration, appeared. Additionally, the time necessary for the acceleration of the flame was well simulated (50 ms in the calculations, 3 to 30 ms. in the experiments). In the ***choked*** propagation area (vertical sections), the results of the experiments and the calculations for the flame velocity agree.

While the flame penetrates in the tube, the combustion products are discharged into the atmosphere via the venting orifice. The propagation of the flame inside the channel implies that combustion products should traverse a longer distance until they are discharged suffering an enhanced ***head loss***. Its value may be expressed with the formula $\Delta P = \int K\rho v^2 dx$, along the tube length, being K an empirical coefficient. The results of numerical experiments carried out with diverse flow velocities in the range 1-30 m/s allow approximating K with the value 1.4.

The existence of obstacles creates an additional complexity in the flow pattern. The obstacles produce, for the laminar regime propagation, a change in the total surface of the flame and thus of the total species consumption. As the obstructions are gradually reached, cyclic oscillations in the velocity of the discharge products (see Fig. 4) as well as in the pressure (order of tens of Pa, peak of ~ 340 Pa, see Fig. 5) will appear. Pressure variations (see Fig. 5) slightly compress and decompress the part of the tube filled by the reactants. The volume filled with reactants could be understood as a close cylinder, or a ***drum***, in which the flame actuates as an oscillating piston. Nevertheless, no shock waves develop during the whole ***quasi-laminar*** regime.

The total hydrodynamic resistance of the products to be discharged in the atmosphere grows ***quasi*** linearly as the flame penetrates inside the tube (see Fig. 5, thick line). When the resistance is comparable with the pressure peaks created by the flame, the products have difficulties to be discharged and a part of them are accumulated inside the tube. The reactants receive an enhanced compression and thus an increased compression-decompression cycle is triggered. The flame suffers an additional acceleration and traverses an augmented distance per oscillation. Some significant flow appears ahead of the flame. If during this displacement an obstacle is overcome, the burning rate will be enlarged by the turbulence created by the barrier and the flame starts to burn in the turbulent regime. The burning rate, the compression of the reactants and the hydrodynamic resistance are thus enhanced. Next compression-decompression cycle will drive the flame to a very intense acceleration that will ultimately finish in the ***choked*** regime.

The coupling between the phenomena described in the previous paragraphs is complex. The small, but unavoidable, differences between the different experiments cause the different timing of the flame acceleration of the test carried out with 40% of venting.

5. Conclusions

The circumstances producing the rapid and sharp acceleration of the flame in tubes burning from its open end were analyzed. Three experiments were simulated in order to study the acceleration of the flames with different venting ratios. The dynamics of the combustion process was qualitatively reproduced by the numerical simulations. The results obtained showed a long term stage of laminar flame propagation followed by a rapid transition to the sonic flame. It was numerically ascertained that the resistance of the tube behind the flame front is a key mechanism triggering the transition from laminar to sonic flame within 50 ms (or 3-30 ms in the experiments). The acceleration process involved a pure hydrodynamic and oscillating mechanism but no shock waves. The same mechanism might be responsible for the detonation initiation in obstructed channels with end venting in cases of more reactive mixtures or larger tube diameters.

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