DEFLAGRATION-TO-DETONATION TRANSITION IN CYLINDRICAL BUBBLES WITH AN UNSTABLE BOUNDARY

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It is demonstrated by means of experimental modeling of burning a propane–oxygen mixture in cylindrical bubbles in polyvinylchloride tubes containing obstacles in the form of single drops of water and balls that the transition from deflagration to nonideal detonation occurs both in front of the obstacle and behind it.

Introduction

The present work deals with various issues of gas combustion in quasi-cylindrical bubbles in a liquid aimed at the development of principally new heat generators and water propulsion plants [1, 2]. Experiments with separate cyclic injection of a combustible gas and oxidizer into water revealed instability of explosions in bubbles from one shot to another. The hypothesis is very simple: either a deflagration combustion mode or a deflagration-to-detonation transition (DDT) occurs. Ignition is provided by a spark generated by a usual car plug. These features do not allow unique interpretation of results obtained for cyclic modes of pulsed burning of gases in a liquid. Therefore, the challenge is to elucidate the mechanisms of the DDT in bubbles of combustible mixtures in water.

The DDT was studied by many researchers [3, 4]. Various types of the accelerated transition in metallic shock tubes and special facilities were investigated. However, the possibility of generation of transitional processes in liquid shells was not considered in those studies. The present paper describes the results of experimental investigations of the transition from deflagration to nonideal detonation as applied to elastic and liquid shells. Transitional processes for a propane–oxygen mixture in a polyvinyl chloride (PVC) shock tube with "obstacles" in the form of water drops and individual steel and polystyrene balls are considered.

Arrangement of Experiments

It is known from previous experimental investigations [2] that the DDT was not obtained in steady smooth bubbles. This phenomenon was observed in dynamically blown bubbles. Figure 1 shows a typical photograph of a quasi-cylindrical bubble with a gas before the explosion in the case of injection of gases from two linear slots into water with separate injection of the combustible gas and oxidizer.

It is clearly visible in the photograph (see Fig. 1) that the bubble has a corrugated rough boundary which can be interpreted as the Rayleigh–Goertler instability with the height of "waves" on the bubble boundary up to 3 mm. These results stimulated investigations based on model experiments aimed at elucidating the role of such boundaries on the processes of gas combustion inside the bubble.

A cylindrical bubble was modeled by transparent PVC tubes with an inner diameter of 6–8 mm and a length of 160–200 mm. The arrangement of the experiments is illustrated in Fig. 2 which shows the place where the process was initiated by a spark in the gap between a tungsten bung and a needle.

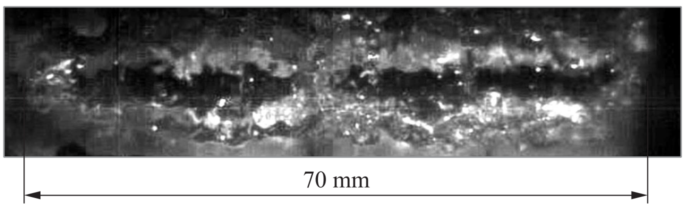

Figure 1 Typical photograph of a quasi-cylindrical bubble with a gas before the explosion in the case of injection of gases from two linear slots into water with separate injection of the combustible gas and oxidizer

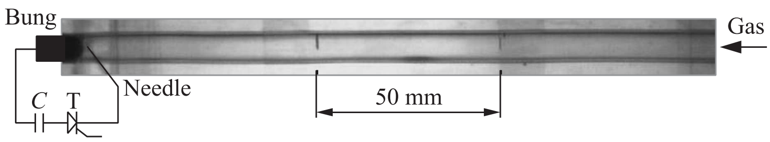

Figure 2 The arrangement of the experiments

A high-voltage spark-induced breakdown between the bung and the needle was provided by an electric discharge of a capacitor with a capacitance $C = 4\ \mu$F charged up to $U = 0.4$ kV. The discharge was controlled by a thyristor (T) with a subsequent discharge to the primary winding of a TVS-90 transformer. The spark energy did not exceed 0.3 J. In this configuration, the experiments were performed in a stoichiometric propane–oxygen mixture with the initial pressure of 10^5 Pa.

Obstacles in the form of water drops or balls made of steel or polystyrene foam were placed into the middle part of the tube. The combustion processes in the tube were recorded by a MotionXtra HG-LE digital videocamera with a speed of 50 000 frame/s.

Experimental Results

Figure 3 shows the results of high-speed filming of the processes of ignition, combustion, and beginning of the DDT in the case of impingement of the compression wave (CW) onto the drop. At the end of these records, there is a schlieren picture of the tube before combustion initiation (in a unified scale) where the water drop inserted into the tube is marked by the arrow.

In this variant, the DDT occurred in the region where the water drop was located.

The experiments with smaller drops and with steel or polystyrene foam balls (with diameters $d = 2.5$ mm) were also performed. As a whole, the qualitative pattern of the processes was similar to that obtained in the experiment with a water drop shown in Fig. 3.

It should be noted that the CW is formed at the late stages, in 200 μs after the spark-induced discharge on the average, at distances of 40–60 mm from the left bung.

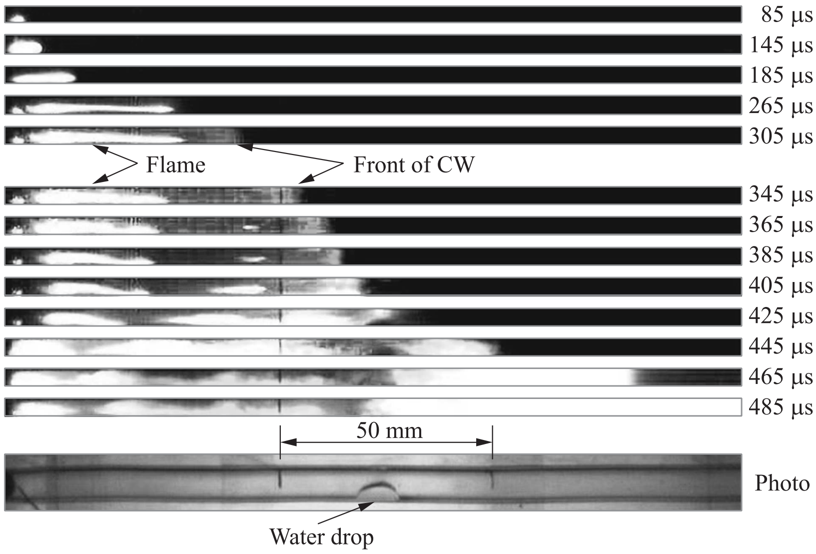

Figure 3 The results of high-speed filming of the processes of ignition, combustion, and beginning of the DDT for $C_3H_8 + 5O_2$ in the case of impingement of the CW onto the drop

It follows from Fig. 3 and similar records that impingement of the CW onto the drop (the time instant of 405 μs in Fig. 3) leads to a flash of combustion and, possibly, detonation (425 μs). After that, within 20 μs, a similar process starts to develop behind the drop, and the front is accelerated up to 1.8 km/s.

Figure 4 shows the measured velocity of the front of the first torch of the flame (on the left) and its quenching (lower branch) and the front of shock wave enhancement with a transition to detonation (upper branch). The beginning of the drastic change in the shock front velocity to the right, i. e., the beginning of detonation, corresponds to the drop location coordinate, X = 87–95 mm (the time instant of 425 μs in Figs. 3 and 4).

The experiments with an empty tube (with no obstacles) showed that detonation did not develop over the entire tube length. The detonation appeared only at the opposite end of the bung regardless of the

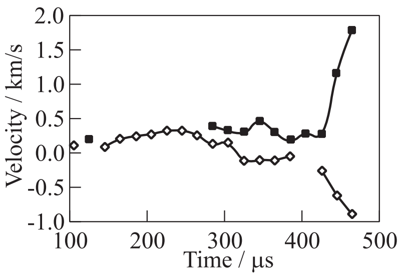

Figure 4 The measured velocity of the front of the first torch of the flame for $C_3H_3 + 5O_2$ (on the left) and its quenching (lower branch) and the front of shock wave enhancement with a transition to detonation (upper branch)

bung material (steel, brass, or water). The detonation front was developed toward the flame torches, thus enhancing the luminance of the latter. The luminescent front on the right was easily traced. However, it was difficult to measure the detonation front velocity in the left part of the picture for the experiments with obstacles because the initial flames disguise the front. It should be noted, nevertheless, that the luminescent front arrives at the left end face of the tube earlier than at the right end face. The results obtained in experiments in the tube at a length of 160 mm without obstacles showed that the velocity of the detonation wave front over the gas with flame torches reached 2 km/s. An interesting fact should be noted: the polystyrene foam ball that was not fixed in the tube remained at the same place after detonation development. No ball melting was visually observed.

Brief Analysis of Results

The following important fact should be noted: the low-velocity detonation is developed both ahead of the obstacle and behind it after the CW impinges onto the obstacle. The detonation regime ahead of the obstacle is developed earlier approximately within 20 μs with a certain probability (sometimes, the opposite situation is observed).

It follows from the experimental data that the CW is formed in the tube after a certain volume of the gas burndown and expands in the form of a piston with combustion products; an accelerating shock wave is formed on the front of this piston. At this stage, combustion in the left part of the tube is incomplete. For this reason, the detonation also propagates in the opposite direction from the obstacle. Taking these facts into account, one can conventionally assume that the low-velocity detonation regime is developed almost symmetrically to both sides from the obstacle within the time resolution of the videocamera.

Concluding Remarks

The mechanisms of instability of burning combustible gases in water were experimentally identified and studied.

Based on modeling combustion of a propane–oxygen mixture in a PVC tube with obstacles, it was demonstrated that the transition from deflagration to nonideal detonation occurs on these obstacles regardless of their physical properties.

It is demonstrated by means of experimental modeling that the transition from deflagration to nonideal detonation occurs both in front of the obstacle and behind it.

References

1. Teslenko, V. S., A. P. Drozhzhin, R. N. Medvedev, and I. S. Batraev.2014. In-water gas combustion in linear and annular bubbles. *Thermophys. Aeromech.* 21(4):479–488.
2. Medvedev, R. N., A. P. Drozhzhin, and V. S. Teslenko. 2016. Thrust generation by pulse combustion of gas in a submerged chamber. *Int. J. Multiph. Flow* 83:232–238.
3. Frolov, S. M. 2008. Fast deflagration-to-detonation transition. *Khim. Fiz.* 27(6):31–44.
4. Vasil'ev, A. A. 2015. Cellular structures of a multifront detonation wave and initiation (review). *Combust. Explo. Shock Waves* 51(1):1–20.