Flame Acceleration in the Hydrogen-based Microfoam

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1 Introduction

Hydrogen by itself represents perspective fuel with high thermal efficiency and calorific value, herewith providing the smallest amount of greenhouse emissions in the combustion process. However, in practice hydrogen storage and transportation face challenges related to safety issues. Hydrogen is one of the most reactive combustible fuels and once mixed with oxidizer it is characterized by high probability of deflagration-to-detonation transition (DDT) leading to formation of devastating detonation waves. One of the possible solutions for safe hydrogen utilization is to burn hydrogen gas as a part of aqueous foam [1]. It is reasonable to assume that detonations in such hydrogen-based foams are also possible, but foams possess the ability to efficiently attenuate shock waves that makes detonation propagation in the foam less dangerous compared to gaseous detonation. Another promising direction of studies is application of hydrogen bubbles in micro- and nanocombustion technologies. Thus, perspective microcombustors can be developed on the basis of the spontaneous ignition phenomenon in nanobubbles containing mixture of hydrogen with oxygen [2]. However, for today it seems more practical to utilize hydrogen as an addition to traditional hydrocarbon-based fuels. For instance, blends of hydrogen with diesel and biodiesel fuels allow reducing emission and increasing fuel conversion efficiencies [3,4]. Effective hydrogen addition to hydrocarbon fuels is also possible in a form of nanobubbles that can significantly decrease fuel consumption levels and improve engine brake power [5]. The utilization of emulsion fuels is expected to provide lesser yield of harmful pollutants such as carbon and nitrogen oxides as well as polyaromatic hydrocarbons and soot. All these components are forming in the high-temperature region behind the flame front, so it is quite promising to utilize emulsions to intensify energy losses due to the phase transitions, thereby freezing the reactions responsible for harmful pollutants formation.

Foams and foamed emulsions are of great scientific interest as they are widely used in our everyday life. With regard to the combustion, foams are well known as its inhibitors. However, as a result of reactive gaseous mixtures bubbling into the water with surfactant addition one can obtain combustible foam. Combustible processes taking place in those foams are being investigated in [6-8]. Research shows that in such reactive foams various transient combustion regimes are possible including detonation waves [8]. Moreover, the presence of the liquid phase in such systems causes acceleration of the transition to detonation [8]. The observation of detonation onset at relatively short distances indicates that the process of flame acceleration in the foam is related not to the geometrical scales of the reactor but to the spatial

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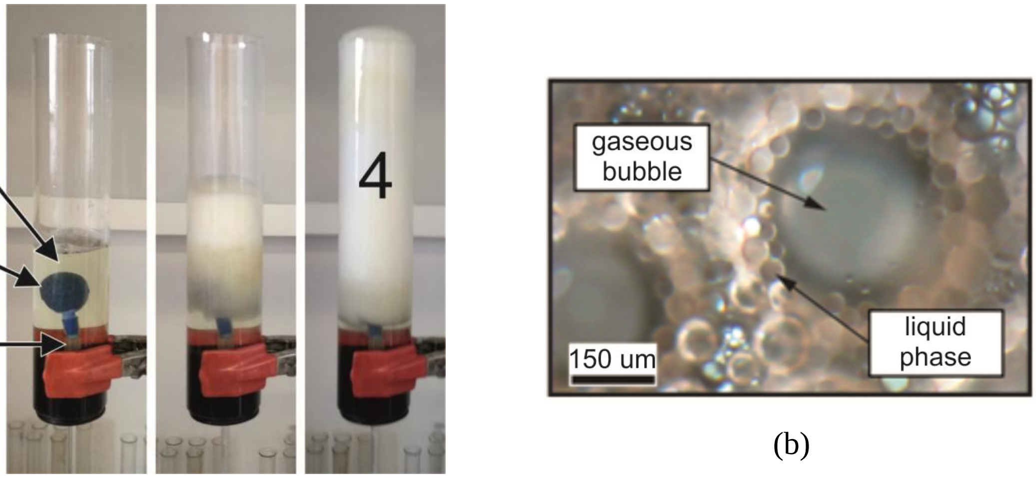
scales characterizing the foam structure (such as the characteristic bubble diameter). Due to this the transient processes of flame acceleration and transition to detonation in the foam can be analyzed independently on the reactor geometry. So, it is reasonable to conclude that such a system is rather convenient for analysis of critical chemical conditions for different transient regimes of combustion. For example, one can add a liquid hydrocarbon as a part of aqueous phase which will be evaporated and affect the reaction kinetics in the flame zone. In such a way, the relative effect of hydrogen and hydrocarbons can be easily analyzed separately at all the stages of flame development in the foamed emulsion bubbled with hydrogen-oxygen mixture. It should be noted that in case of the foam containing liquid hydrocarbons as a part of liquid phase the appropriate choice of the hydrocarbons favors the temporal-spatial splitting of the zones of hydrocarbon and water evaporation [9]. Herewith, the hydrocarbons begin to evaporate exactly ahead of the flame front while water evaporates later, mainly in the region of combustion products. Therefore, the pure effect of hydrocarbon-hydrogen mixture combustion can be studied in such a reactor. It is also important to note that contemporary surfactants allows preparation of foams and foamed emulsions [10] much more stable than those considered in early papers [6-8]. Moreover, appropriate choice of the foam components and preparation technique allows considering the combustible foams in a quite wide range of parameters [11].

In view of issues discussed above, it is fairly interesting from applied point of view to elaborate technology for studying gaseous (hydrogen) combustion inside the reactor on the base of aqueous foam. Furthermore, the clear understanding and interpretation of the processes taking place in such systems are of fundamental interest. Therefore, the main goal of this work is to analyze the peculiar behavior of the reactive system containing both the reactive gaseous (hydrogen) and liquid fractions. In particular, the paper analyzes experimentally the combustion regimes taking place in the foams and foamed emulsions bubbled with hydrogen-oxygen mixtures. All the stages of transient combustion including flame acceleration, transition to detonation and detonation decay are considered.

2 Experimental setup

To prepare the foam the technique proposed in [11] was applied. Water solution of stabilizer was foamed via bubbling of hydrogen-oxygen mixture of given composition directly inside the tube where the combustion was subsequently studied (Fig. 1a). Prepared hydrogen-microfoams possessed the following parameters. The foam expansion ratio was equal to 10. The average diameter of bubbles was about 300-400 μm. Hydrogen-oxygen mixture was prepared using the hydrogen as a product of Zn+HCl reaction and the oxygen-nitrogen mixture containing 90 % of oxygen and 10 % of nitrogen. The hydrogen content in the mixture was varied in the range from 0 to 100 %$. The microphotography of the considered combustible foam is presented in (Fig. 1b).

After the preparation the foam was ignited at the top open end of the tube with the use of pilot flame that leaded to the flame formation and propagation downwards in the direction of closed bottom end of the tube. The flame speed was measured with the use of high-speed camera Photron FASTCAM SA-4 (10000 fps, 10 μs shutter speed). Here and below the term “flame speed” is used to determine the speed of the fastest point of the flame surface. The term “total burning rate of the foam” is used to determine flame speed averaged over the whole tube length. To estimate the total burning rate values the experiments were repeated at least five times.



(a)

(b)

Figure 1. Left (a): Tube feed with the foam, 1 – tube for hydrogen-oxygen inflow, 2 – porous element, 3 – water solution of stabilizer, 4 – prepared foam, Right (b): microphotography of the foam.

3 Results and discussion

Let us consider the process of flame propagation through the aqueous foam bubbled with hydrogen-oxygen mixture observed in the experiments. Figure 2 illustrates the sequence of photographs corresponding to different stages of flame propagation while figure 3a shows the history of the flame speed estimated on the basis of photography series.

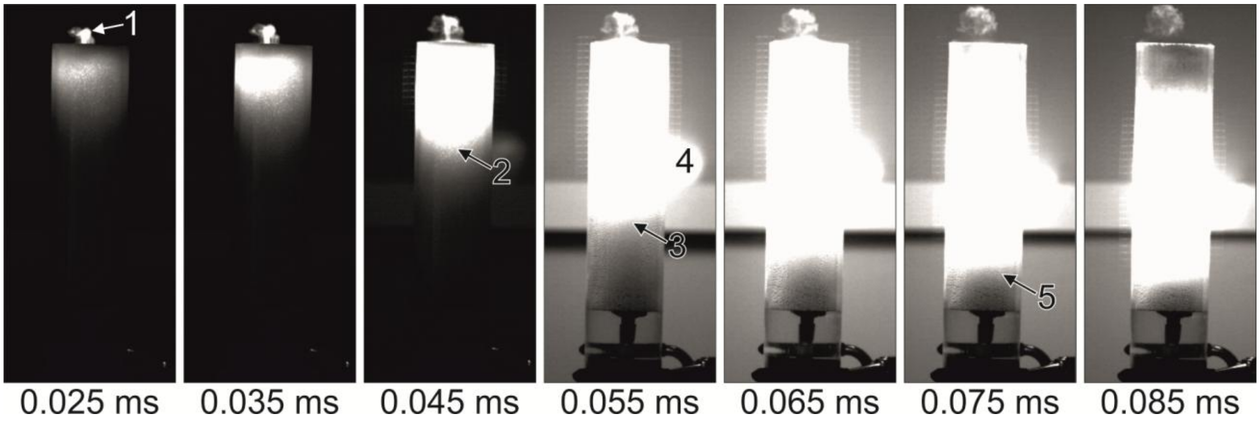
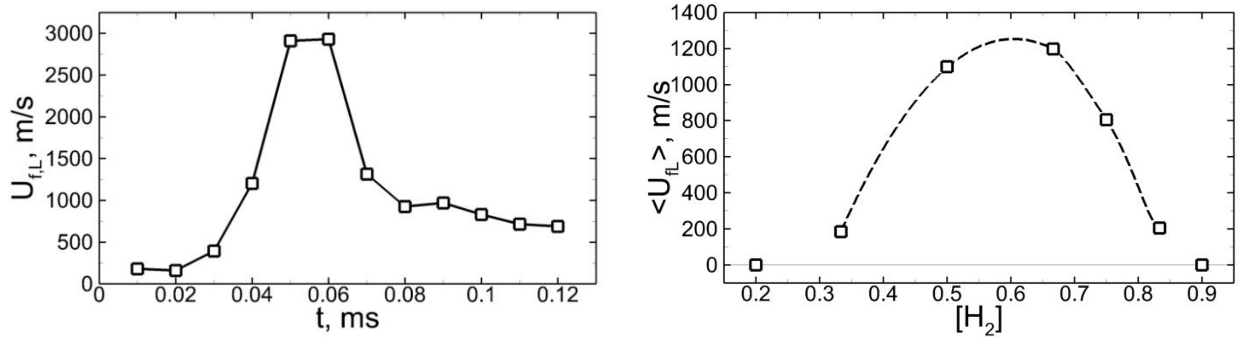


Figure 2. Sequence of photographs demonstrating the flame evolution in the microfoam bubbled with stoichiometric hydrogen-oxygen mixture. 1 – Pilot flame, 2 – Accelerating flame, 3 – Front of quasi-detonation, 4 – Flare, 5 – Slow wave.



(a) (b)

Figure 3. Left (a): History of the flame speed in the same foam as in Fig. 2. Right (b): Total burning rate of the foams bubbled with hydrogen-oxygen mixtures of different composition.

According to the obtained data (Figs. 2 and 3a) three basic stages of flame evolution in stoichiometric hydrogen-oxygen mixture can be distinguished. On the first stage, near exponential flame acceleration is observed. On the second stage, the flame transits into the fast detonation-like wave. Herewith, the flame speed increases locally even higher than the CJ detonation speed in gaseous hydrogen-oxygen mixture. It should be noted that this stage lasts a relatively short period after which the flame decelerates and the process transits into the third stage of slow flame propagation.

Acceleration of the flame can be related to the following mechanisms. Let first consider the mechanism of foam decay. The foam represents a multiphase structure of gaseous bubbles separated by thin liquid films and relatively thick liquid clusters formed due to the films intersection (Plateau borders). The most probable mechanism of foam decay is the fracture of films in the thinnest region under the heat or dynamic impact. Herewith, the foam decays into the large droplets of the order of Plateau borders size. Here it is interesting to note that in case of the foam considered here, the bubbles size, as well as the Plateau borders size (~0.7 of the bubble size), are of the order of the flame thickness. In stoichiometric hydrogen-oxygen at normal conditions, it can be estimated as ~0.2-0.3 mm. At the same time, the bubbles size in the considered foam is estimated as 0.3-0.4 mm while the thinnest region of the film can be estimated as 0.04 mm or even less. Under the action of the heat flux from the propagating flame such thin liquid film can be evaporated in the preheat zone of the relatively thick flame front. At the same time, this film can decay due to the hot gases expansion. As a result, the foam decays ahead of the propagating flame front. In view of this one can consider the flame propagation in the foam as propagation through the water mist consisting of the water droplets regularly spaced in space. Here, water droplets size equals to the Plateau border thickness (~0.2-0.3 mm) while the distance between droplets is of the order of bubbles diameter (~0.3-0.4 mm). In such conditions, the flame front occurs to be permanently perturbed by the disturbances with wavelength of the order of flame thickness. Here it should be noted that such a wavelength represents the shortest mode responsible for development of the hydrodynamic instability [12]. It is well known that according to the linear theory of instability the shorter is the perturbation of the flame front the greater is the increment of the instability growth [12]. Due to this in considered case the flame permanently subjected to the short wavelength perturbations accelerates exponentially, which can be one of the possible reasons of the observed exponential acceleration on the first stage. At the same time Fig. 2 shows that during this stage the flame develops similar to the pure gaseous case [13]. On the early stage it spreads outwardly from the ignition source, after which a so-called "finger" flame is forming. In gaseous mixtures these stages are also characterized by the exponential acceleration that is related to the gasdynamical mechanisms as well.

The process of flame acceleration is always accompanied with the compression of the medium ahead of the flame front [14]. It should be, however, noted that in case of foam combustion the formation of shock wave ahead of the flame in the foam region is less plausible than in pure gases. Firstly, it is related to the attenuating properties of the foam which transmits compression waves with a rather high resistance [15]. On another hand, the stage of flame acceleration is quite short and the shock wave has no time to be formed. At the same time the compression wave causes gas heating and dynamic impact on the aqueous films in the compression region ahead of the flame front. This can be a possible cause of foam decay in this region both due to the dynamic impact and to the heated gas expansion. Moreover, the compression waves generated by the accelerating flame in the gap between its front and foam surface partly reflect from the foam surface that induces additional compression in the pre-flame zone. As a result the stage of flame acceleration in the foam occurs to be similar to one in the gaseous mixtures. In particular, the flame accelerates due to gasdynamic mechanisms and causes permanent compression of the medium in the pre-flame zone. Finally, such a behavior can lead to the detonation formation, which propagation possibly determines the second stage of the process characterized by the supersonic flame speed (Fig. 3a). In Fig. 2 a shiny flare can be observed in the region of detonation onset. Herewith, it is interesting to note that the flare is not symmetric that indicates that detonation arises locally, e.g. in the vicinity of the leading point of the flame like in gaseous mixture [16]. This flare itself has purely optical origins and the tube remains unbroken. The intensification of luminosity, as well as luminosity itself, most probably is related to the rate of oxidation of hydrocarbon part of stabilizer.

As it was already mentioned above, strong shocks attenuate when interacting with the foam. Moreover, it is reasonable to assume that joint dynamic impact and heating caused by the shock driving the detonation leads to the foam decay and droplets fragmentation. Small water droplets formed in this process define significant heat losses in the induction zone that in turn determines detonation decay. As a result the transition to the third stage takes place during which the combustion front continues to propagate involving in the flow ejected due to the explosive character of the previous stage of flame evolution. The characteristic flame speed on this stage is ~600 m/s. Similar behavior was observed recently [9] in the combustible foamed emulsions where the explosive boiling of liquid phase caused ejection of droplets-vapor mixture accompanied with the generation of compression wave, which propagation velocity was measured as ~300 m/s (much higher than the effective sonic speed in the foam [17]).

The same patterns are observed in the whole range of hydrogen-oxygen foam flammability. The flame accelerates and transits to detonation, which subsequently decays if the tube is long enough. Therefore, the total burning rate depends on gaseous mixture composition non-monotonically (Fig. 3b).

4 Conclusions

The paper presents new results on the flame propagation through the aqueous microfoam bubbled with hydrogen-oxygen mixture. It is shown that such a flame is able to accelerate and even propagate with significantly high (nearly detonation) speed. This high-speed regime, however, occurs to be unstable and decays into the fast wave dragged by the flow generated in the transient process of flame acceleration. Presumably all the peculiarities are fully related to the structure of the foam so such a reactor can be used to analyze features of combustion independent on the reactor geometry.

Acknowledgements

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