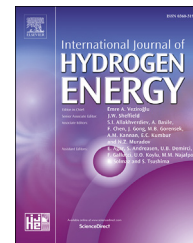




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Combustion of hydrogen–oxygen microfoam on the water base

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ABSTRACT

On the basis of experimental study the paper analyzes the process of combustion wave propagation in the hydrogen–oxygen microfoam on the water base. Combustible microfoam consists of gaseous bubbles dispersed in the water solution of surfactant. Bubbles contain hydrogen and oxygen and their diameters are in the range from 60 to 230 μm . Expansion ratio of the combustible foam is in the range from 8 to 22. The paper establishes the influence of surfactant concentration, glycerol concentration, tube diameter and Shchelkin's spiral on the speed of flame propagation in the foam. It is shown that for considered range of regime parameters the characteristic mode of flame propagation in the semi-opened tube is the accelerated mode. The increase in glycerol content leads to the increase in flame speed. However after certain critical concentration of glycerol the foam loses the ability to burn. Total burning rate depends on surfactant concentration non-monotonically with characteristic maximum. Shchelkin's spiral installed at inner surface of the tube as well as the decrease in tube diameter favor flame deceleration.

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Introduction

The paper represents new experimental data on the combustion of hydrogen–oxygen microfoam on the water base. Considered combustible system is a two-phase medium consisting of gaseous bubbles dispersed in the water solution of surfactant and filled with either hydrogen or oxygen. The study of such combustible foams is of interest due to the set of reasons.

In many ways hydrogen is the perfect fuel [1–7], however its wide utilization is limited with the safety related issues [8–14]. Thus gaseous hydrogen-based mixtures are characterized by high probability of deflagration-to-detonation transition (DDT) [15–19] leading to the formation of detonation waves [20–23]. As a rule the origins of DDT are related

with the phenomenon of flame acceleration [24] which can be determined by a set of factors such as combustible mixture composition [25], its volumetric distribution (e.g. in the form of concentration gradients [26]), channel geometry [27,28] including obstacles [29–31] and perforation of the wall [32,33]. One of the leading roles in flame acceleration and DDT in gaseous hydrogen-based mixtures belong to acoustic and compression waves defining the flame and flow evolution inside closed vessels [34–36]. In such conditions in addition to the flame acceleration and DDT one can observe regimes with oscillations in the flame speed as well defined by the pressure waves.

Here it should be noted that foams are able to absorb efficiently the acoustic perturbations and attenuate shock waves [37]. In view of issue related with elaboration of safe fuel on the hydrogen base the studying of combustion of

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Nomenclature

D	tube diameter
D_L	molecular diffusivity of limiting component
k	coefficient
Le	Lewis number
ΔP	pressure difference between vapor in bubble and surrounding medium at the moment of explosive boiling of liquid
r_w	characteristic size of water drops
S_b	total burning rate
S_L	laminar burning velocity relative to unburned mixture
x	distance down the tube

Greek symbols

δ	characteristic width of the convective–diffusion zone of flame
ρ_v	water vapor density
ρ_f	effective foam density
σ_w	surface tension of the aqueous phase
τ_c	characteristic time during which the considered element is in the convective–diffusion zone of flame
τ_d	time scale of diffusive mixing
τ_v	time of water drops evaporation
χ	thermal diffusivity of gas
ω	velocity of reacting mixture ejection

hydrogen–oxygen foams should be of certain interest. Of course, detonation waves can arise in the combustible foams on the water base as well however they would be much weaker.

On the other hand nowadays there is increase in researchers interest to the microscale combustion [38–41] related with issues of elaboration of microengines [42–44] and microreactors [45–48]. Herewith a set of new non-trivial issues arise related, for example, with the choice of materials both resistant to high temperatures of combustion products and enough technological to produce micro-scale energy systems. The utilization of combustible foams on the water base as fuels seems to be perspective direction for solving the issues of heat resistance of the materials. Water drops forming at the foam decay could favor protection of the equipment surfaces from the overheating. A distinctive feature of this work is the studying of combustible foam containing the bubbles of microscopic scales.

One of the first papers devoted to the combustion of the foams on the water base was the paper by Burgone and Steel [49]. In this work the flame propagation limits were studied for the foam consisting of gaseous bubbles filled with methane–air mixture. The water matrix of the foam represented a water solution of the surfactant. Ref. [50] represented experimental results on flame speed measurements in the water-based foam containing gaseous bubbles filled with hydrogen–air mixture. In Ref. [50] a macrofoam was studied in which diameter of gaseous bubbles was in the range from 1 to 4 mm. It is well known that the increase in the bubbles diameter leads to foam destabilization [51]. Indeed

combustible foams considered in Refs. [49,50] were extremely unstable. Due to this to reduce shrinkage of the foams the flame speed measurements in Refs. [49,50] were carried out in the rotating tube.

Distinctly different type of combustible foams (foamed emulsion) was studied recently in Refs. [52,53]. Foamed emulsion consisted of oxygen bubbles dispersed in the emulsion which represented a water solution of stabilizer with hydrocarbon (o-xylene or cyclohexane) drops suspended in it. In the process of combustion of such a foam the foam decayed into the drops which burned in the oxygen environment. Herewith the flame speed in many ways depended on the mechanism of foam decay. It was found that the mechanism of combustion of such foams differed significantly from that realized in water-based combustible foams containing the bubbles filled with premixture of gaseous fuel with oxidizer.

The aim of this paper is to study the flame propagation in water-based microfoams containing gaseous bubbles filled with hydrogen–oxygen mixture. To reduce bubbles diameter the foam is prepared by chemical method. Herewith hydrogen and oxygen are synthesized via chemical reactions. In such a way the foam is prepared containing gaseous bubbles with diameters belonging to the range from 50 to 230 μm . At this the foam expansion ratio is rather low (from 8 to 22). Such low values of foam expansion ratio mean that the unit volume of the combustible foam contains a significant amount of water. Nevertheless such foams preserve combustibility and demonstrate entirely non-trivial features of combustion. Due to the reduction in the diameter of gaseous bubbles we succeeded in the preparation of sufficiently stable combustible foam with “lifetime” of the order of several minutes. It should be noted that earlier in Ref. [54] the process of hydrogen–oxygen mixture combustion was observed in smaller nanobubbles (~ 100 nm) however the stable combustion wave propagation in such a system was not observed.

Experimental set-up

Method of combustible foam preparation

Combustible microfoam was prepared via chemical method of foaming of water solution of stabilizer (surfactant). The solution was prepared using the distilled water and stabilizer. We used sulfonol (sodium 4-alkyl-2ylbenzene-sulfonate), SDS (sodium dodecylsulfate) and commercial detergent as stabilizers. Sulfonol and SDS are the stabilizers of anionic type. Stabilizers (sulfonol and SDS) were mixed with water and the solution was aged during 24 h until full dissolution of components. Detergent is a mixture of anionic and nonionic stabilizers. Due to the interaction between anionic and nonionic components the foams containing this type of stabilizer occur to be more stable compared with the case of pure anionic stabilizer use. Surface tension was measured using a duNouy ring tensiometer Krüss K20 (Germany) with error 0.1 mN/m. The measurements were carried out at temperature of 23 °C.

We used zinc powder and hydrochloric acid (31%) to produce hydrogen filling the gaseous bubbles of the foam ($\text{Zn} + 2\text{HCl} = \text{ZnCl}_2 + \text{H}_2\uparrow$). Oxygen was produced via

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