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Combustion of emulsion-based foam

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ABSTRACT

Results of the experimental and theoretical investigations of flame propagation in foams based on hydrocarbon-in-water emulsions are presented. Experimental data refer to the combustion of foams consisting of oxygen bubbles with diameters within 70–130 microns distributed in *o*-xylene-in-water and cyclohexane-in-water emulsions. Flame propagation velocities were determined for the combustion of various foams in semi-open ended tubes and a foam layer in the atmosphere, and it was established that oscillating regimes of flame propagation in these systems were possible. A decrease in the content of fuel in the initial emulsion leads to decrease in the amplitude of pulsations in the velocity of flame propagation. Estimates of the flame front propagation velocity (flame speed) in foams were obtained and the limits of flame propagation were established. A qualitative analytical model is proposed that describes the experimentally observed phenomenon of flame speed oscillations.

1. Introduction

Foams are disperse systems consisting of a base liquid with distributed gas bubbles. Depending on the volume fraction of the gas phase, these systems are classified as bubbly liquids (with a volume gas fraction below 10%) and foams. If the foam contains reacting components, chemical reactions are principally possible and the formation of a combustion wave can take place under certain conditions. A chemical reaction can take place both in the gas and in the liquid phase. An example of such a gas–liquid system with a reaction proceeding inside the liquid phase is offered by the oxidation of cyclohexane [1]. The effective reaction rate in this case is controlled by the rate of chemical reaction rather than by the diffusion resistance of medium. The process is carried out in the liquid phase by means of hot air dispersion with rather insignificant volume content of the gas. If the reaction rate is high, the interaction between reactants takes place predominantly in a diffusion film occurring at the gas–liquid boundary. In this case, from the standpoint of effective use of the reactor volume, the process is expediently carried out in the froth regime. This article presents the results of our investigation of the combustion of foamed emulsions. The interest in studying these foams is related to the possibility of creating technological processes for the synthesis of thermodynamically unstable substances by means of their quenching in contact with a cold liquid.

This paper considers neither issues pertaining to the combustion of bubbly liquids [2,3] nor tasks related to the formation and propagation of detonation waves in foams [4]. One of the first investigations devoted to the combustion of water-based foams was carried out by Burgone and Steel [5] and devoted to analysis of the limits of flame propagation in foams with methane–air gas mixture. In particular, it was established that the concentration limits of flame propagation in foams are narrower than in gas mixtures. The propagation of flame is accompanied by destruction of the foam. At low values of the foam expansion ratio (defined as the ratio of foam volume to the volume of contained liquid), the flame propagates in the form of separate foci (kernels) moving independently of each other, rather than as a flat front. Zamaschikov et al. [6] and Babkin et al. [7] also analyzed the combustion of water-based foams with gas bubbles filled by hydrogen–air and methane–air mixtures. Experimental results for the flame front propagation velocity (flame speed) in foams were obtained for several variable parameters including the foam expansion ratio, stabilizer concentration, acoustic action, and solution viscosity. It was found that, under certain conditions, the burning rate of water-based foams can exceed that of the corresponding gas mixture, which was a rather nontrivial result since water vapor formed upon the evaporation of liquid drops reduces the concentrations of reactants in the combustion zone and, in addition, the temperature in the flame front decreases because of heat losses for the phase transition. It was also established that, as the foam expansion ratio decreased (with increasing water content in the foam), the flame speed increased; in addition, the development of unstable combustion regimes was observed for certain compositions of the gas mixture. The common characteristic feature in investigations

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Nomenclature

Latin

B_f	Transfer number
B_w	Defined by Eq. (3)
C_f	Foam friction (resistance) coefficient
c	Heat capacity of gas–drop mixture
c_l	Heat capacity of liquid
c_{vw}	Heat capacity of water vapor
D	Tube diameter
D_L	Molecular diffusivity of limiting component
D_{max}	Maximum diameter of fuel drops
E_a	Effective activation energy
f_f	Defined by Eq. (21)
f_w	Coefficient
G_w	Rate of water drop evaporation
Le	Lewis number
L_f	Latent heat of vaporization for fuel
L_w	Latent heat of vaporization for water
m_0	Initial concentration of fuel
N_0	Number of microbubbles per unit volume of liquid
N_w	Number of water drops per unit volume
ΔP	Pressure difference between vapor in bubble and surrounding medium at the moment of explosive boiling of liquid
Q	Chemical energy release
q	Defined by Eq. (5)
R	Universal gas constant
R_b	Radius of vapor bubble
r_w	Average water drop radius
S	Flame speed in foam
S_b	Total burning rate
$S_{b(n)}$	Total burning rate at time moment t_n
$\tilde{S}_b$	Maximum total burning rate of foam corresponding to complete evaporation of fuel drops
S_L	Laminar burning velocity relative to unburned mixture
S_*	Minimum flame speed
T_0	Initial temperature
T_b	Maximum flame temperature
T_{b*}	Minimum temperature on the flame front
T'_b	Temperature on the flame front
T_s	Saturation temperature
ΔT	Liquid overheating relative to saturation temperature
ΔT_b	Difference between flame front temperature and initial foam temperature
ΔT_{b*}	Defined by Eq. (26)
ΔT_{ex}	Liquid overheating at the moment of its explosive boiling
t	Time
x	Distance down the pipe

Greek

α	Defined by Eq. (19)
β	Defined by Eq. (20)
γ	Defined by Eq. (5)
ε	Foam expansion ratio
λ	Thermal conductivity coefficient of the gas
λ_l	Thermal conductivity of liquid
ρ	Gas-drop mixture density
ρ_f	Effective foam density
ρ_l	Liquid fuel density
ρ_v	Water vapor density
φ_{cr}	Critical water content for flame quenching
φ_{ex}	Critical vapor content at the moment of explosive boiling of liquid
φ_w	Volume content of water in the emulsion
χ	Thermal diffusivity of gas
χ_f	Thermal diffusivity of foam
χ_l	Thermal diffusivity of liquid
ω	Velocity of reacting mixture ejection

[5–7] was the analysis of combustion in water-saturated foams with high foam expansion ratios (from 30 up to 1600) and gas bubbles diameters in a millimeter range, where both fuel and oxidizer were only concentrated in the gas bubbles.

This paper presents results of the experimental research of combustion in absolutely different class of foams based on emulsions, such that only oxygen was contained in the gas bubbles. In contrast to [5–7], where the experiments were performed with foams obtained by the dispersion of fuel gas mixtures in aqueous solutions of stabilizers, foams in the present work were prepared by a special chemical method in order to reduce the diameters of gas bubbles. According to this, hydrogen peroxide added to an aqueous solution of stabilizer decomposes in the presence of a catalyst with the formation of oxygen. Using this method, we managed to create foams with a characteristic gas bubble diameters within 70–130 µm. Svetovoy et al. [8] detected reaction in a hydrogen–oxygen mixture in even smaller bubbles of a nanoscale level, but a combustion wave in this system was not observed. The experimental results presented below were obtained for the flame speed in foams with variable hydrocarbon content and type (cyclohexane and *o*-xylene), and variable stabilizer type. The combustion of foams was studied in tubes of various diameters and in a foam layer in the atmosphere. A simple qualitative model is proposed for estimating the flame speed in the foam and it is shown that oscillating regimes of foam combustion can take place.

2. Theoretical analysis

2.1. Slow regime of foam combustion

In this investigation, by combustible foam we imply a system of the following type: oxygen-filled gas bubbles are bounded by thin films of liquid, the main fraction of which is concentrated in the Plateau borders. The main attention is devoted to the combustion of dry foams, in which the volume fraction of liquid does not exceed 5%. Gas bubbles contain only oxygen, while the liquid phase represents a macroemulsion of water with dispersed hydrocarbon drops.

In studying the combustion of foams, we can separate two limiting cases with respect to the flame speed: slow and fast combustion regimes. In the case of a slow combustion, the main role in flame propagation is played by the thermal-diffusion and kinetic processes, while the gasdynamic effects do not significantly influence the total burning rate. By the order of magnitude, the rate of slow combustion corresponds to the laminar flame speed in premixed gases. During combustion, the heat flux is transferred from the flame front to cold layers of the foam. The evaporation of a liquid film separating bubbles and/or the presence of temperature gradient [8] leads to destruction of the foam. The mechanism of foam decay is extremely complex and ambiguous. The rupture of one film in the foam can lead to breakage of the neighboring film as a result of the appearance of local fluctuations in the pressure and surface tension via so-called “collective” effect [9]. The foam breakage leads to the formation of sprayed drops of water,