



The role of explosive boiling in the process of foamed emulsion combustion



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ABSTRACT

The paper analyzes the role of explosive boiling of liquid phase on the process of foamed emulsion combustion. Combustible foamed emulsion represents a multiphase system consisting of oxygen bubbles and hydrocarbon drops dispersed in the water solution of stabilizer. A certain interest to study such systems is determined by the fact, that even at significant water content in the foam it preserves its combustibility. If the temperature in the combustion zone occurs to be higher than a certain critical level, then the defining role in the process of flame propagation will belong to the process of explosive boiling of liquid phase. Herewith the flame speed is determined not by the heat transfer or diffusion of active centers but by the intensity of explosive boiling. On the basis of phenomenological conception the criterion is derived for determination the conditions of explosive boiling of liquid phase of the foam. Foamed emulsion combustion is accompanied by its decay and water drops formation. The dependence of water drops size on the foam composition is obtained with the use of photography of combustion products multiphase flow. It is found out that the flame acceleration due to explosive boiling is accompanied with a decrease in water drops diameter that in turn favors the increase in the intensity of heat losses in the combustion zone and subsequently results in the flame deceleration.

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1. Introduction

One of the promising areas of contemporary energetics is to utilize water as a component of hydrocarbon-based fuel [1–12]. This issue is due to number of reasons. One of these reasons is related with the necessity of NO_x emission reduction. The water leads to the temperature decrease in the combustion zone and as a result to the prevention of nitrogen oxidation [13–15]. Moreover, one is able to regulate rheological properties of hydrocarbon fuels with the water addition. For example, in such a way the quality of coal tar spraying could be increased. Due to these features the combustion of emulsion fuel (oil-in-water or water-in-oil) attracts a significant research interest [1,16–19].

The mechanism of emulsion fuel combustion depends on the set of factors (drops size of dispersed phase [24], volumetric content of hydrocarbon in the emulsion [20] and emulsion drop size [20]). At certain conditions the combustion of emulsion drops could be accompanied with micro-explosion [3,21,22], when a secondary fragmentation of the drop takes place as a result of its boiling. Especially this phenomenon is relevant in terms of increase in

combustion intensity and completeness. Note that micro-explosion phenomenon takes place only in the water-in-oil emulsion. Moreover, the boiling temperature of oil should be higher than boiling temperature of water. Intensity of micro-explosion depends on a set of factors such as diameter of water droplets as a part of emulsion drop [23].

Recently, as a development of the problem of emulsion fuel utilization the new type of combustible system – foamed emulsion (or foamulsion) was proposed [24–27]. Combustible foamed emulsion represents a multiphase system consisting of oxygen bubbles distributed in the water solution of stabilizer, in which the oil drops are dispersed. The interest to study such combustible systems is defined by the fact that they possess a set of unique properties. For example, the foamed emulsion containing 90 wt% of water preserves combustibility that makes it rather promising type of fuel [25,26], especially, when utilizing the foamulsion in the micro power devices [28] and in the issues related with utilization of oil products spilled on the water surface.

An important role in the process of foamed emulsion combustion could belong to the explosive boiling of liquid phase [27]. In this case the speed of flame propagation through the foam is determined mainly not by the heat transfer or diffusion of active centers but by the intensity of explosive boiling. In view of this one could significantly change the flame speed in the foam by regulation of

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Nomenclature

C_l	heat capacity of liquid, J/(kg K)
D	tube diameter, m
E_a	effective activation energy, J/kg
L_w	latent heat of vaporization for water, J/kg
N_b	number of vapor bubbles in the unit volume of liquid phase, 1/m ³
P	pressure, Pa
ΔP	pressure difference between vapor in bubble and surrounding medium at the moment of explosive boiling of liquid, Pa
Q	chemical energy release, J/m ³
R	universal gas constant, J/(kg K)
R_b	radius of vapor bubble, m
r_f	radius of fuel drop, m
r_w	average water drop radius, m
r_g	radius of gaseous bubble in the foam, m
S_b	total burning rate, m/s
T_b	combustion temperature, K
ΔT_l	water superheat relative to saturation temperature, °C
ΔT_{ex}	superheat of liquid phase relative to the saturation temperature at explosive boiling, °C

t	time, s
v	velocity, m/s
Z	pre-exponential term in the Arrhenius expression, s ⁻¹

Greek symbols

α	coefficient defined by Eq. (4), K
λ_w	thermal conductivity of water, W/(m K)
ρ_l	liquid fuel density, kg/m ³
ρ_f	foam density, kg/m ³
ρ_v	water vapor density, kg/m ³
σ_w	surface tension of the aqueous phase, N/m
τ_d	characteristic hydrodynamic time of foam decay, s
τ_{ex}	characteristic time of liquid phase heating until foam decay, s
ν	kinematic viscosity of liquid, m ² /s
φ_l	volumetric content of liquid phase in the foam
χ	thermal diffusivity of gas, m ² /s
ψ_{ex}	critical volumetric vapor content corresponding to the foam decay

boiling process. For example, in [29] it was shown that the use of magnesium oxide microparticles, which in fact represent heterogeneous centers of vapor bubbles nucleation, could lead to the increase in the flame speed by almost an order of magnitude.

The main goal of this paper is the complex analysis of the effect of liquid phase boiling process on the combustion of foamed emulsion. The paper analyzes conditions of explosive boiling in combustible foams in a wide range of their compositions. On the basis of phenomenological conceptions the criterion is derived for explosive boiling of liquid phase of the foam. It is obtained that if the temperature inside the combustion zone occurs to be higher than a certain critical value then the flame speed will be mainly determined by the intensity of explosive boiling. In turn, the temperature inside the combustion zone is defined not only by the intensity of heat release in the process of chemical reactions but also by the heat losses. Heat losses at the flame front are affected by such factors as tube diameter [27], presence of obstacles inside the tube [27] and the evaporation intensity of water drops formed in the process of foam decay. In view of this, the problem of water drops parameters determination is rather relevant in terms of basic theory elaboration for foamed emulsion combustion. In this paper the data on the dependence of water drops sizes on the foam composition and the flame speed is obtained by means of photography of multiphase flow with help of laser lighting. Note that the experimental results on the determination of water drops diameter in the region of combustion products are presented in the paper for the first time. It is obtained that the diameter of water drops depends on the intensity of explosive boiling. Due to this correlation the oscillating regime of flame propagation could possibly arise in the process of foam combustion.

2. Experimental section

2.1. Method of foamed emulsion preparation

The process of foamed emulsion preparation was realized into two basic steps. First the oil-in-water emulsion was prepared, which was subsequently foamed with the use of chemical method. N-nonane, n-heptane and isooctane (>99% purity, Aldrich Chemi-

als) with boiling temperatures at atmospheric pressure: 150.8, 98.4 and 99.3 °C, respectively were used as hydrocarbons. Maximal burning rates of premixed isooctane-air and n-heptane-air mixtures do not exceed values of 0.8 and 0.9 m/s correspondingly [30]. To prepare emulsion a water solution of stabilizer was used. The solution was prepared by stirring the distilled water with a stabilizer. Commercial detergent and sodium dodecylsulfate (SDS) were used as stabilizers. Commercial detergent is a surfactant of mixed type consisting of anionic and nonionic surfactants. SDS is a surfactant of anionic type. Surface tension was measured using a duNouy ring tensiometer *Krüß K 20* (Germany) with error 0.1 mN m⁻¹. Measured coefficients of interphase tension are presented in Table 1. The emulsion was prepared by stirring water solution of stabilizer with oil in the vessel of 300 mL with the use of two-paddle Teflon stirrer during 10 min (stirring intensity, 200 rpm). The size of heptane drops was controlled using microphotographs. The emulsion was foamed with the use of oxygen released in the process of hydrogen peroxide decomposition $2\text{H}_2\text{O}_2 = 2\text{H}_2\text{O} + \text{O}_2 \uparrow$. To do this, hydrogen peroxide (50% purity) was stirred with emulsion, and the ammoniac solution of copper sulfate was used as catalyst. The diameter of gaseous bubbles in the foam was estimated with the use of microscope *Bresser Biolux NV* (Germany). In the process of experimental study the foam expansion ratio was determined, which represents a ratio of the foam volume to the volume of liquid phase as a part of the foam.

Table 1
Surface and interfacial tensions at 23 °C.

	Surface tension (mN/m)
Water + stabilizer	
Water + SDS	32.2
Water + detergent	29.9
Pure hydrocarbon surface tension	
Heptane	19.5
Isooctane	18.3
Nonane	22.1
Water + stabilizer/hydrocarbon interfacial tension	
Water + detergent/heptane	3.0
Water + SDS/isooctane	3.5

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