



Full Length Article

Foamed emulsion – Fuel on the base of water-saturated oils



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HIGHLIGHTS

- Combustible foamed emulsion is a mixture of bubbles and oil drops in water base.
- Foamed emulsion is a new type of fuel.
- Foamed emulsion is able to burn at water content of 90 wt%.
- Magnesium oxide particles causes increase in total burning rate of the foamed emulsion.
- Flame speed is higher in less stable foamed emulsion.

ARTICLE INFO

Article history:

Received 1 February 2017

Received in revised form 1 April 2017

Accepted 27 April 2017

Keywords:

Water-saturated fuel

Foamed emulsion

Foam stability

Solid particles

Flame speed

ABSTRACT

Combustible foamed emulsion is a mixture of oil drops and oxygen bubbles in an aqueous matrix. Such combustible foams represent a perspective type of fuel in whose production water-saturated hydrocarbons can be utilized directly. Experimental results show that even at water content of 90 wt% there still is opportunity of flame propagation in the foam. The paper analyzes an influence of magnesium oxide particles and type of surfactant on the stability of foamed emulsion and the speed of flame propagation in it. The use of magnesium oxide micro-particles promotes the increase in flame speed especially at heightened volume fraction of oil in the initial emulsion. At the same time it causes destabilization of the foam. The use of anionic surfactant instead of surfactant of the mixed type leads to decrease in combustible foam stability and increase in flame speed.

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1. Introduction

Foamed emulsion or foamulsion represents a multiphase system consisting of gaseous bubbles dispersed in an aqueous emulsion [1]. Such dispersed systems are widely applied in our everyday life that determines an interest to their study [2,3]. Recently a brand-new application of foamed emulsion as a fuel was proposed in [4]. Considered combustible foam consists of oxygen bubbles and hydrocarbon (cyclohexane or o-xylene) drops dispersed in the water solution of surfactant. Foaming of the emulsion is carried out via chemical method that consists in hydrogen peroxide decomposition accompanied with oxygen release. It is found experimentally that combustible foamed emulsion obtains a set of unique properties. For example, the flame front propagation is possible even in the foam containing 90 wt% of water although the water is an inhibitor of combustion. Note that the process of flame propagation in the foamed emulsion differs sufficiently from the combustion of emulsion drops in the oxidizer environment [5].

Such combustible systems provide new opportunities of water-saturated oils utilization as a fuel avoiding the stage of components separation. Herewith the procedure of fuel production on the base of foamed emulsion can be rather simple. In the first stage a surfactant is added to the water-saturated oil and the mixture is stirred to obtain oil-in-water emulsion with specified dispersed composition of drops. In the second stage the emulsion is foamed due to the dispersing of oxygen (air) in it. By adjusting the foam expansion ratio (the ratio of volumes of the foam itself and the liquid contained in the foam) one can change the properties of the combustible foam in rather wide range.

Bubbly gas-liquid systems formally can be divided into two basic classes: bubbly liquid (with volumetric gas contain <10%) and foams. Nowadays one actively studies the opportunity of bubbly liquids utilization as fuels, for example, for technology of hydrogen nanobubbles dispersion in the gasoline fuel [6,7]. At the same time foams are traditionally perceived as inhibitors of combustion [8]. Nevertheless foamed emulsions have a great potential to be used as fuels especially due to the opportunity to utilize water-saturated oils for their preparation avoiding the stage of refining.

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Nomenclature

Latin

B	bridging coefficient (N^2/m^2)
d_d	maximal diameter of fuel drop (m)
E	entry coefficient of oil drop on the interface (N/m)
N_{MgO}	number density of MgO particles in the emulsion (m^{-3})
S	spreading coefficient (N/m)
S_b	total burning rate (m/s)
\dot{S}_b	maximum total burning rate of foam corresponding to complete evaporation of fuel drops (m/s)
$S_{b(t)}$	total burning rate at time moment t_n (m/s)
\dot{S}_b	limit flame speed (m/s)
S_L	laminar burning velocity relative to unburned mixture (m/s)

ΔT_b difference between flame front temperature and initial foam temperature ($^{\circ}C$)

Greek

α	coefficient
β	coefficient
σ_o	surface tension of the oil phase (N/m)
σ_w	surface tension of the aqueous phase (N/m)
$\sigma_{w/o}$	oil/water interfacial tension (N/m)
ω	velocity of reacting mixture ejection (m/s)

A significant drawback of the foams when using them as fuels is an intrinsic instability determined by excess surface energy. To avoid foam shrinkage the surfactants are used. However, the surfactants cannot generally fully prevent ageing of foams and emulsions with time through gravitational foam drainage or emulsion creaming, as well as through coarsening (or Ostwald ripening). Thereby foamed emulsions as fuels should be utilized during short time period directly after preparation.

Taking into account the relevance of problems related with foam contraction this paper considers both problems of combustion and stability of foamed emulsions prepared on the base of heptane or o-xylene. The paper analyzes the influence of foam surfactant (anionic and mixed) on the velocity of combustion wave propagation and on the foam stability. One of the perspective ways for foams stabilization is the usage of solid particles which can promote formation of an incompressible armor around the bubbles [9,10]. It prevents the liquid flowing from the films between bubbles and from the Plateau borders of the foam. This paper also analyzes the influence of magnesium oxide particles on the stability of foamed emulsion and on the velocity of combustion wave propagation in it.

2. Experimental section

2.1. Materials

Distilled water, oil (heptane or o-xylene) and surfactant were used for emulsion preparation. Boiling temperatures of heptane and o-xylene at atmospheric pressure are 98.4 and 144.4 $^{\circ}C$ correspondingly. Sulfonol or commercial detergent were used as surfactants to stabilize foam and emulsion. Sulfonol (sodium 4-alkyl-2ylbenzene-sulfonate) is a surfactant of anionic type. Detergent is a surfactant of mixed type representing a mixture of anionic and nonionic surfactants. Surface tension was measured using a duNouy ring tensiometer KrüssK20 (Germany) with error 0.1 $mN m^{-1}$. Measured coefficients of interphase tension are presented in Table 1. As solid particles we used MgO powder with wide disperse composition in the range from 100 nm to 2 μm (Fig. 1c).

2.2. Foamed emulsion preparation

Emulsion was prepared via stirring of surfactant water solution with oil inside the 300 ml reactor using the two-bladed mixer. The stirring was carried out during 10 min with frequency of 80 rpm. Characteristic size of oil drops in the emulsion was in the range from 8 to 57 μm . Foaming of the emulsion was carried out by

Table 1
Surface and interfacial tension at 23 $^{\circ}C$.

Water + stabilizer	Surface tension (mN/m)
Water + detergent	29.3
Water + sulfonol	28.3
Pure hydrocarbon surface tension	
O-xylene	27.7
Heptane	19.5
Water + stabilizer/hydrocarbon interfacial tension	
Water + detergent/o-xylene	1.9
Water + sulfonol/o-xylene	0.2
Water + detergent/heptane	3.3

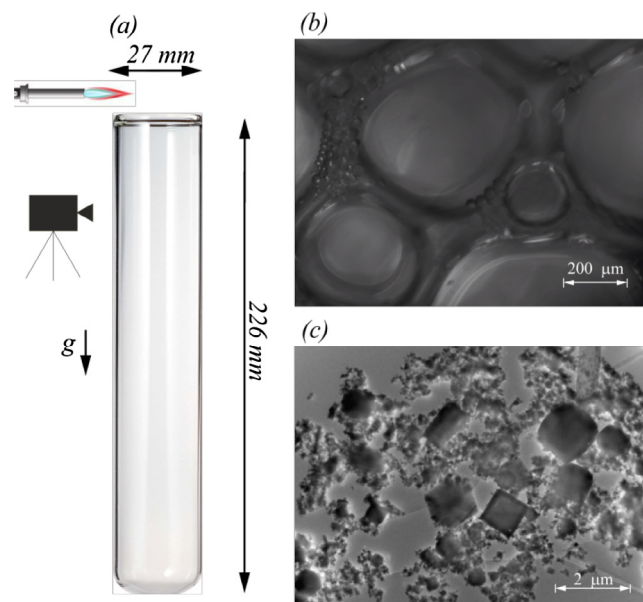


Fig. 1. (a) Semi-opened tube in which the combustion of the foam was studied; (b) microphotograph of the foamed emulsion; (c) microphotograph of the MgO particles.

chemical method through hydrogen peroxide decomposition. Herewith ammoniac solution of copper sulfate was used as a catalyst. The process of hydrogen peroxide decomposition provided oxygen release via $2H_2O_2 = 2H_2O + O_2$. Diameter of gaseous bubbles in the foam directly after preparation was in the range from 80 to 140 μm . It should be noted that diameter of gaseous bubbles depended weakly on the foam composition. Microphotograph of

the combustible foam is presented in Fig. 1b). Depending on the content of MgO particles and oil in the emulsion the expansion ratio of the foam was different (Fig. 2).

2.3. Monitoring the ageing of foamed emulsion

Foam stability was estimated on the base of foam shrinkage rate. Foam height fraction was determined as a ratio of the current height of foam column (at given time instant) to the height of foam column at initial time instant.

2.4. Flame speed measurements

Flame speed was measured in the vertical tube with opened top end (Fig. 1a). Foaming of the emulsion was carried out directly inside the tube. Combustible foam was ignited at the opened end of the tube by pilot flame. Measurement of flame propagation speed was carried out with the use of high-speed video camera (Motion Pro X3, United States). Term “flame speed” was used to determine the propagation speed of the fastest point of the flame front. Term “total burning rate” was used to determine a flame speed averaged over the whole length of the tube.

3. Results and discussion

3.1. Stability of the foamed emulsion

Any foam is unstable by its nature, in view of the excessive interfacial free energy. Foams can be stabilized by using surfactants, which increase the surface viscosity and surface elasticity of liquid films between gas bubbles [11]. These stabilizers cannot fully prevent the foam shrinkage that takes place due to gravitational drainage and coarsening or Ostwald ripening. Surfactants can represent ionic and nonionic components or their mixtures. In addition solid particles can be used to stabilize foams and emulsions [11]. The present work employed anionic surfactant (sulfonol) and detergent representing a mixed surfactant system. In mixed systems, the interaction between ionic and nonionic components produces additional stabilization of foam due to the formation of condensed films.

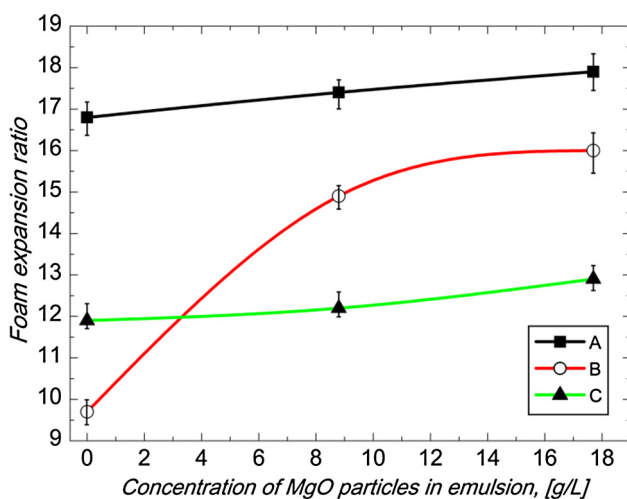


Fig. 2. Dependence of foam expansion ratio on MgO particles content in the emulsion. Foam was prepared from heptane, water (3.3 mL), detergent (1.7 mL), hydrogen peroxide (3 mL), and ammonia solution of copper sulfate (1.3 mL, 1.05 mol/L). Volume fraction of the heptane in the emulsion was (A) 2.1%; (B) 17.7%; (C) 34.9%.

Under certain conditions, hydrocarbon drops dispersed in water can favor decay of foams and act as “defoamers” or “antifoams” [12]. Nevertheless, foamed emulsions exist and sometimes even exhibit high stability [1]. The high stability is intrinsic to foamed emulsions with high oil content (>70 vol.%) [1]. However, the present work did not consider such systems, and the maximum content of heptane in emulsion did not exceed 34.9 vol.%. The mechanism of stabilization of foamed emulsions is controlled by the surface viscosity of the film, thermodynamic factors (e.g., disjoining pressure), and the accumulation of oil drops inside Plateau borders. The change in the foam stabilizer type quite significantly influences the foam structure and stability. In many ways the stability of foamed emulsion depends also on the parameters of oil dispersed phase in the emulsion: oil volume fraction, drop size and oil phase density [2].

The stability of foamed emulsion can be estimated in terms of the entry coefficient of oil drop on the interface

$$E = \sigma_w + \sigma_{w/o} - \sigma_o \quad (1)$$

The thermodynamic analysis shows [13] that negative values of E correspond to complete wetting of the oil drop by the aqueous phase. As a result, oil with negative E is expected to be rather inactive as antifoam [13]. Vice versa, positive value of E corresponds to the condition according to which the oil drop (lens) enters the surface between oxygen and water (Fig. 3a).

To estimate foam breaking efficiency Rooss [14] introduced the concept of the spreading coefficient

$$S = \sigma_w - \sigma_{w/o} - \sigma_o \quad (2)$$

If $S > 0$ then oil is able to destabilize the foam. The correctness of this criterion is still under discussion, however in number of cases the use of this criterion occurs to be effective [12].

According to [13] the bridging coefficient is introduced as

$$B = \sigma_w^2 + \sigma_{w/o}^2 - \sigma_o^2 \quad (3)$$

Positive value of the bridging coefficient corresponds to the formation of unstable bridge inside the liquid film between bubbles. Possible mechanisms of the process of liquid films collapse are: “bridging-stretching” (Fig. 3b) or “bridging-dewetting” (Fig. 3c). “Bridging-dewetting” mechanism implies that once the oil bridge is formed between the two surfaces of the foam film, this bridge is “dewetted” by the aqueous phase.

Taking into account the data from Table 1 the coefficients (1)–(3) for foam with detergent equal to $E = 3.5 \text{ mN m}^{-1}$, $S = -0.5 \text{ mN m}^{-1}$, and $B = 0.095 \text{ mN}^2 \text{ m}^{-2}$. For foam with sulfonol these values are $E = 0.8 \text{ mN m}^{-1}$, $S = 0.4 \text{ mN m}^{-1}$, and $B = 0.034 \text{ mN}^2 \text{ m}^{-2}$. The foam with detergent is characterized

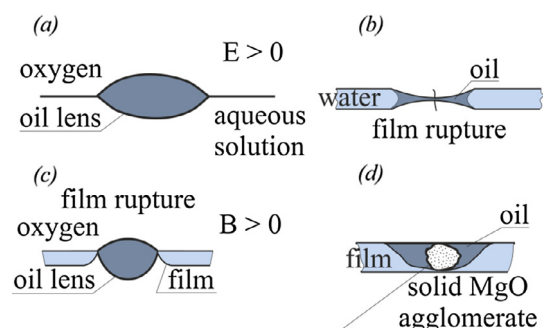


Fig. 3. (a) Oil drop enters the interfacial surface; (b) liquid film decay via “bridging-stretching” mechanism; (c) liquid film decay via “bridging-dewetting” mechanism; (d) the lens “penetration depth” can be significantly increased (at the same oil volume) by a solid MgO agglomerate [12].

(in contrast to the case of sulfonol) by a negative value of the spreading coefficient, which must favor higher stability. Indeed, the foam with sulfonol is very unstable and susceptible to decay within several seconds after formation (Fig. 4). The expansion ratio of the foam with detergent and sulfonol is 10.8 and 8.8, respectively, which shows that a change in the stabilizer type does not lead to significant change in the foamability. It should be noted that the foamability depends not only on the surfactant type and its concentration, but is also significantly influenced by the method of foam formation (which was the same for both stabilizers used in this work).

3.2. The role of particles in stabilizing foamed emulsions

In addition to surfactants an important role in foam stability can belong to solid particles [15–18]. This paper analyzes influence of MgO particles on both the foam stability and the flame speed. Note that mixtures of oil and hydrophobic solid particles often have much higher antifoam efficiency in comparison with each of the individual components (oil or solid particles) taken separately [12].

Experimental results represented in Fig. 5 show that MgO particles promote destabilization of the foam at MgO particles concentration in the emulsion 14 g/L (case C, Fig. 5). On the one hand it is determined by the decrease in stabilizer concentration due to adsorption of the surfactant molecules on the solid particles surface [13]. On the other hand MgO particles are able to form agglomerates that favors decay of the liquid films between bubbles of the foam (Fig. 3d) [12]. On the contrary at negligibly low concentration MgO particles favor increase in foam stability (case B, Fig. 5). This can be explained by the fact that MgO particles prevent liquid flowing from the foam at negligible affect related with stabilizer adsorption on the particles surfaces.

3.3. Foam expansion ratio

Foam expansion ratio depends significantly on the volumetric content of heptane in the emulsion (Fig. 2). Heptane is antifoam therefore foam expansion ratio increases with decrease in heptane concentration (Fig. 2). Foam expansion ratio increases with MgO particles concentration however the rate of such influence depends on the heptane concentration in the emulsion (Fig. 2). The fact that MgO particles favor increase in foam expansion ratio is due to

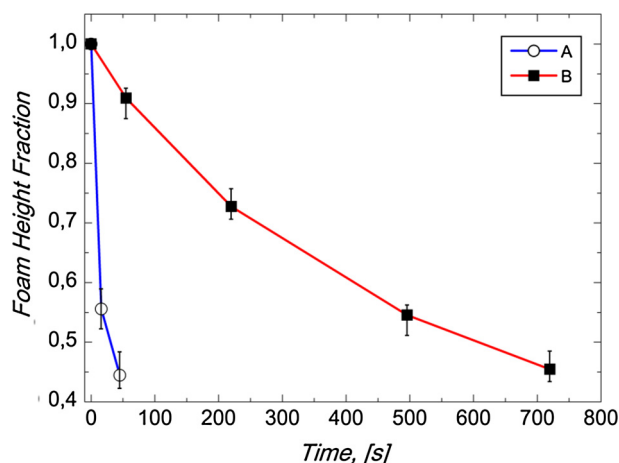


Fig. 4. Foamed emulsion height as a function of time. Foam is prepared from o-xylene (0.5 mL), water (2 mL), hydrogen peroxide (1 mL), and ammonia solution of copper sulfate (0.8 mL, 1.05 mol/L). (A) sulfonol (25.6 g/L), foam expansion ratio, 8.8; (B) detergent (18.6 vol.%), 10.8.

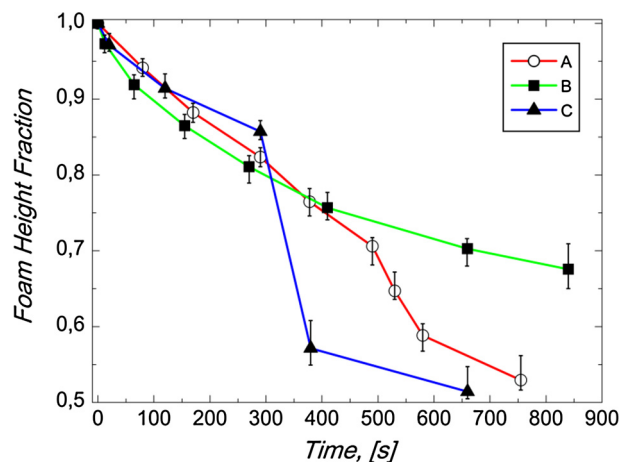


Fig. 5. Foamed emulsion height as a function of time. Foam is prepared from heptane (5 mL), water (3.3 mL), detergent (1.7 mL), hydrogen peroxide (3 mL), and ammonia solution of copper sulfate (1.3 mL, 1.05 mol/L). (A) Content of MgO particles in the initial emulsion, 0 g/L, foam expansion ratio, 11.9; (B) 7 g/L, 12.2; (C) 14 g/L, 12.9.

stabilizing effect of particles causing decrease in liquid flowing from the foam (case B, Fig. 2). At sufficiently high content of heptane in the emulsion the concentration of stabilizer decreases due to the adsorption of surfactant molecules on the oil/water and particle/water interfaces. In view of this on the one hand MgO particles favor foam stabilization and on the other – it's destabilization. Due to this at sufficiently high content of heptane in the emulsion the increase in MgO particles concentration does not lead to notable increase in foam expansion ratio (case C, Fig. 2). At low volumetric concentration of heptane in the emulsion the destabilizing role of oil drops is small and the foam expansion ratio is mainly determined by the amount of gas generated in the process of hydrogen peroxide decomposition.

3.4. The role of MgO particles in foam combustion

3.4.1. Total burning rate of the foam

According to the obtained results (Fig. 6) the total burning rate of the foam increases with the MgO particles content in the initial

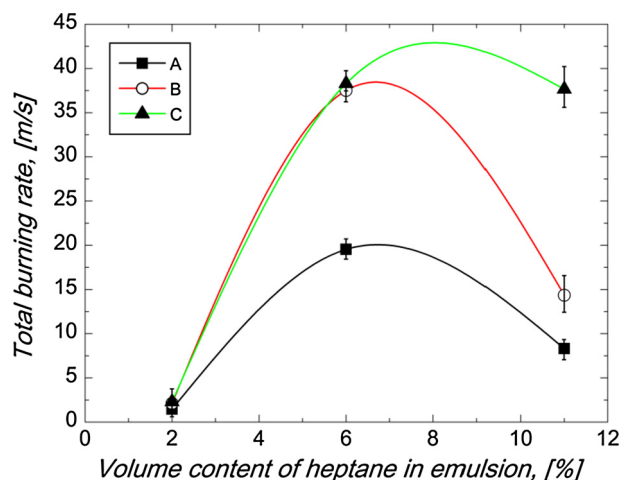


Fig. 6. Dependence of total burning rate on volume content of heptane in emulsion at varying content of MgO particles: (A) MgO content in the emulsion is 0 g/L; (B) 8.8 g/L; (C) 17.7 g/L. Foam is prepared from water (3.3 mL), detergent (1.7 mL), hydrogen peroxide (3 mL), and ammonia solution of copper sulfate (1.3 mL, 1.05 mol/L).

emulsion. At small volumetric content of heptane in the emulsion (less than 6%) the increase in total burning rate with MgO particles concentration is limited. Total burning rate does not depend on MgO particles concentration starting already from 8.8 g/L (Fig. 6).

The mechanism of particles influence on the total burning rate is ambiguous. On the one hand solid particles promote increase in foamability (Fig. 2) that is determined by additional foam stabilization due to formation of incompressible armor around the bubbles and corresponding slowdown in liquid flowing out from the films between bubbles. On the other hand it should be noted that total burning rate of foamed emulsion depends on the expansion ratio of the foam (Fig. 7) which in turn depends on the MgO particles content (see previous section). In general case dependence of total burning rate on the foam expansion ratio is not monotonic. The fact that total burning rate of the foam increases with expansion ratio seems to be quite obvious. Indeed, the larger is expansion ratio of the foam the lower is water content in the volume of combustible mixture that favors decrease in heat losses from the flame front. Due to decrease of heat losses the temperature of the flame front increases that in turn leads to the increase in the flame speed. The experimental fact of total burning rate increase with decrease in expansion ratio (Fig. 7, case A) cannot be explained in the same manner. The explanation is related with phenomena of flame deceleration discussed below.

3.4.2. Flame acceleration

To substantiate the experimental results it is necessary to consider a mechanism of flame acceleration. Indeed, the total burning rate of the foam of ≈ 40 m/s (Fig. 6) is sufficiently higher compare with laminar burning velocity of heptane/oxygen gaseous mixture without water vapors (≈ 5 m/s). Such high combustion rates are determined by the mechanism of flame acceleration associated with explosive boiling of liquid phase of the foam [4]. Herewith the velocity of flame front propagation is determined not by the heat transfer or diffusion of active centers but by the velocity of reacting mixture ejection at explosive boiling of liquid phase of the foam. In more details the mechanism of considered process is as follows. Heat flow from the flame front heats the liquid phase of the foam. Fluctuational mechanism of nucleation leads to formation of supercritical nuclei in the superheated liquid [19,20]. On the base of these nuclei vapor bubbles start to grow. The liquid film between bubbles becomes thinner as the radius of vapor bubbles grows. As the film thickness achieves a certain critical value the foam is collapsing [21]. This leads to formation of the flow of vapor

and drops which transfer a reacting mixture to the cold layers of the foam causing their ignition.

According to the concept of the flame leading point [22] the total burning rate is determined by the propagation velocity of the fastest point of the front. Therefore total burning rate can be estimated as $S_b = S_L + \omega$. Mechanism of flame acceleration via explosive boiling of liquid is characterized by a positive feedback. Indeed, as flame speed increases the larger heat flow is transferred to the cold layers of the foam. This leads to the increase in attainable superheating of the liquid phase at the instant of its explosive boiling. The reason is following. The larger heat flow from the combustion zone is the larger part of the heat is spent on liquid superheat relative to the saturation temperature rather than on phase transition that is related with limited rate of vapor bubbles growth. The pressure inside vapor bubbles increases with superheat of the liquid. Therefore there is corresponding increase in the velocity of reacting mixture ejection at explosive boiling that in turn causes further increase in the flame speed. On the basis of such reasoning one can obtain the following relation between flame speed values at sequential time instants [4]:

$$S_{b(n+1)} = S_L + \alpha S_{b(n)}^{1/3} \tag{4}$$

The process of sustained flame acceleration can be illustrated on the base of Eq. (4). Curve AB in Fig. 8a represents a right hand side of Eq. (4). As flame speed increases there is a rise in intensity of reacting mixture ejection due to explosive boiling of liquid phase of the foam. Reacting mixture ejection leads to burning kernels formation in the cold layers of the foam. The ignition impulse from these kernels is transferred over the whole section of the tube. Fig. 9c represents experimental data on accelerating regime of flame propagation in the foam. One can observe a monotonic increase in the flame speed from 5 m/s to 50 m/s.

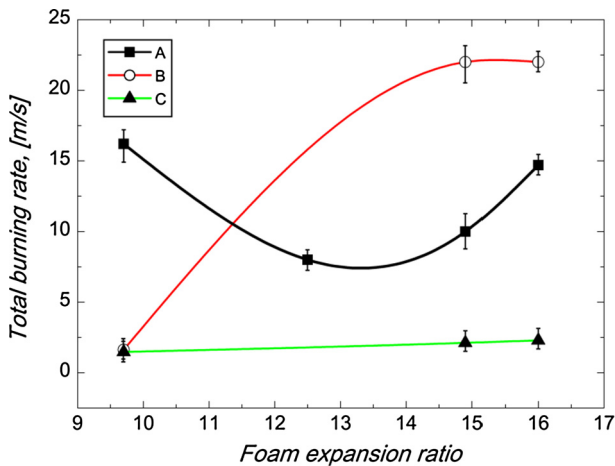


Fig. 7. Dependence of total burning rate on foam expansion ratio: (A) heptane content in the emulsion is 17.7%; (B) 34.9%; (C) 2.1%.

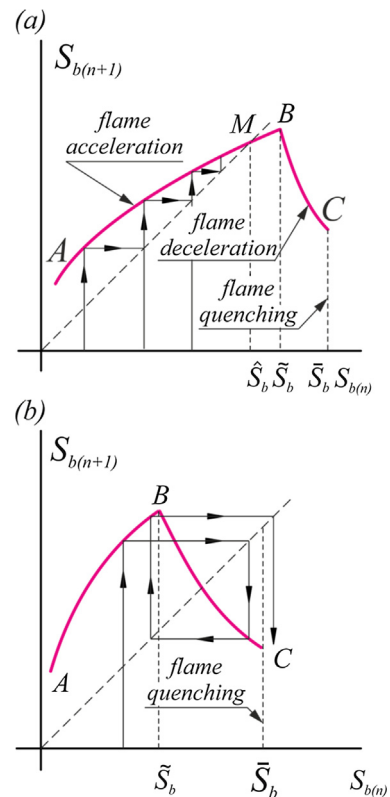


Fig. 8. (a) Sustained process of flame acceleration; (b) oscillatory regime of flame speed evolution followed by the flame quenching. Curve AB is described by right hand side of Eq. (4), BC – by right hand side of Eq. (5).

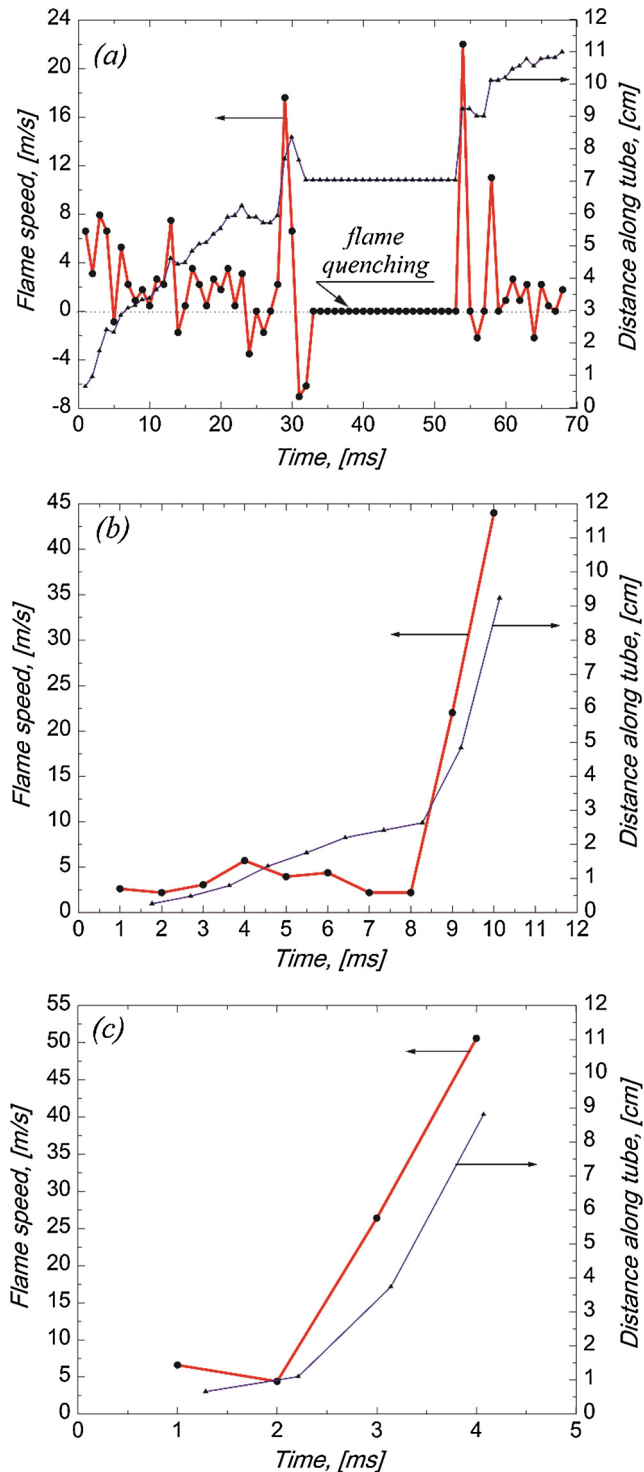


Fig. 9. Plots of the flame speed and distance traveled vs. time at different content of MgO particles. Foam is prepared from heptane (5 mL), water (3.3 mL), detergent (1.7 mL), hydrogen peroxide (3 mL), and ammonia solution of copper sulfate (1.3 mL, 1.05 mol/L): (a) MgO particles content in the emulsion, 0 g/L, total burning rate, 1.62 m/s, foam expansion ratio, 11.9; (b) 11.9 g/L, 9.24 m/s, 12.2; (c) 7 g/L, 22 m/s, 12.9.

3.4.3. Flame deceleration

In the process of flame propagation the foam decays with formation of water drops, fuel drops and/or emulsion drops. If the fuel drops are sufficiently small ($<10 \mu\text{m}$) then they will evaporate inside the convective-diffusion zone of flame [23,24], mix with

oxygen and burn down in the vapor flame. Higher flame speed determines shorter time during which the fuel drops occurs in the convective-diffusion zone of flame (this time is proportional to S_b^{-2}). Meanwhile time necessary for drop evaporation depends on drop diameter as d_d^2 . Therefore if the flame speed becomes higher than some certain value $S_b > \tilde{S}_b \sim d_d^{-1}$ then the largest fuel drops will not have time to be evaporated in the convective-diffusion zone of flame. As a result the temperature of the flame front decreases and at some certain conditions the flame quenches [4]. If the inequality $S_b > \tilde{S}_b$ is true then the increase in flame speed will be followed by the decrease in ejection velocity of the reacting mixture that can be explained as follows. The increase in the flame speed leads to the decrease in fuel concentration in the vapor flame. Corresponding decrease in the temperature in the combustion zone leads to the decrease in the attainable superheat of the liquid phase at the instant of its explosive boiling. In the considered case the values of flame speed at sequential time instants are connected by the equation [4]:

$$S_{b(n+1)} = S_L + \beta S_{b(n)}^{-1/3} \quad (5)$$

Eq. (5) describes the process of flame deceleration represented by the curve BC in Fig. 8a.

3.4.4. Flame speed oscillations

The mechanism of flame speed oscillations can be substantiated on the base of Eqs. (4) and (5) as it is shown in Fig. 8b. Assume that for certain initial time instant the inequality $S_b < \tilde{S}_b$ is true. This means that all the fuel drops are evaporating in the convective-diffusion zone of flame and the temperature of the flame front achieves its maximum. This corresponds to high intensity of explosive boiling of liquid phase of the foam. Flame accelerates and its speed achieves a new value. If in the process of flame acceleration the flame speed achieves value $S_b > \tilde{S}_b$ then mechanism of flame acceleration will be "switched off" and the flame speed will decrease. The described process can be repeated that would determine the oscillatory regime of flame speed evolution. If in the oscillatory process the flame speed exceeds certain maximal value \tilde{S}_b then the flame will be quenched (Fig. 8b). Vapor flame quenching is determined by the reaching of concentration limits due to incomplete evaporation of fuel drops in the convective-diffusion zone of flame. Experimental data for such a regime of foam combustion is represented in Fig. 9a. In the considered case the flame quenches after its acceleration up to 18 m/s at time instant of 30 μs . Fuel drops are evaporating in the zone of combustion products and after a certain time period (20 μs) combustion wave re-initiation arises via self-ignition. Such a regime of flame propagation in the foam can be defined as "quenching/re-ignition".

3.4.5. Transition between combustion regimes

In superheated liquid the critical nuclei are predominantly formed on the extrinsic particles but not in the bulk of liquid phase [20]. This is due to the fact that heterogeneous work of critical bubble formation is significantly smaller than homogeneous one. According to this the mineral particles (MgO) play a role of nucleation centers in the superheated liquid. Larger number density of MgO particles in the initial emulsion determines larger number of vapor bubbles. The latter favors additional fragmentation of the foam at explosive boiling. One may assume that after the foam decay the diameter of fuel drops depends on number density of MgO particles in the emulsion as $d_d \sim N_{\text{MgO}}^{-1/3}$. If we consider that MgO density equals 3580 kg/m³, average diameter of particles is 1 μm and particles content in the emulsion is 10 g/L then characteristic distance between nucleation centers will be about 10 μm . Therefore, for example, fuel drops of initial diameter of 40 μm

would decrease down to 10 μm due to the fragmentation process at boiling of liquid phase of the foam. One can observe a transition from oscillating to accelerating regime of flame propagation with the increase in MgO particles content (compare Fig. 9a and c). As it is mentioned above the flame speed oscillates due to the incomplete evaporation of heptane drops in the convective-diffusion zone of flame. The limit flame speed value \tilde{S}_b (corresponding to the beginning of incomplete heptane drops evaporation in the convective-diffusion zone) increases with the increase in MgO particles content in the foam as $\tilde{S}_b \sim d_d^{-1} \sim N_{MgO}^{1/3}$. If with the increase in particles content the inequality $\tilde{S}_b < \tilde{S}_b$ becomes true then the oscillating regime of flame propagation will transit into the accelerating one (Fig. 8a). Indeed this theoretical conclusion is confirmed experimentally (compare Fig. 9a and c). The change in combustion zone structure related with the use of MgO particles is clearly observed when analyzing Fig. 10.

3.5. Surfactant influence on the foam combustion

Depending on the type of surfactant at fixed other conditions the flame speed can change considerably (compare Fig. 11a and b). On the basis of comparison of these results with the obtained data on the foam stability (Fig. 4) one may conclude that the flame speed is higher in the less stable foam. Apparently less stable foam causes less resistance to the reacting mixture flow [25]. This favors increase in the velocity of reacting mixture ejection at explosive boiling of liquid and as a result flame speed increases.

An important role in flame acceleration belongs to the size of fuel drops formed after foam decay. As it is noted above the MgO particles play a role of heterogeneous nucleation centers in the superheated liquid so their use can favor additional fragmentation of fuel drops at foam decay and as a result the total burning rate increases. In the considered cases (Fig. 11) the MgO particles are not used and the leading mechanism of vapor nuclei formation in the superheated liquid is a homogeneous fluctuational mechanism of nucleation realizing in one of the liquid phases (water or o-xylene) or at the liquid-liquid interface [26]. In case of predominant nucleation inside the oil drops ($\sigma_w > \sigma_o + \sigma_{wo}$) the boiling of liquid phase of the foam causes formation of smaller fuel droplets compare with the case of predominant nucleation, for example, at the liquid-liquid interface ($\sigma_{wo} > \sigma_w - \sigma_o$) [26]. According to Table 1 in the foam containing sulfonol the supercritical nuclei are formed mainly inside the drops of o-xylene. When the detergent is used they are formed mainly at the interface between o-xylene and water. One can expect that the decay of sulfonol-containing foam would be accompanied with the formation of smaller o-xylene droplets that in turn would favor increase in the total burning rate of the foam.

It is important to note that the process of flame acceleration in the foam determines mechanism of self inhibition. Flame acceleration is related with intensification of explosive boiling of liquid phase that favors foam decay with formation of smaller water droplets. Small water droplets evaporate with greater intensity compare with larger drops. This leads to the more active inhibition of the process of heterogeneous combustion of fuel drops due to the increase in heat losses and the dilution of the reacting mixture

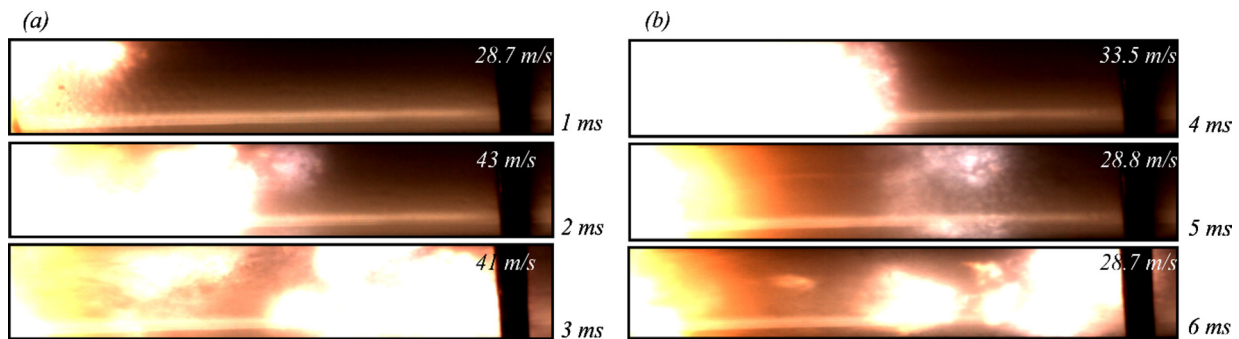


Fig. 10. Structure of combustion zone. Foam is prepared from heptane (0.5 mL), water (3.3 mL), detergent (1.7 mL), hydrogen peroxide (3 mL), ammonia solution of copper sulfate (1.3 mL, 1.05 mol/L): (a) MgO particles content in the emulsion, 11.8 g/L, total burning rate, 37.5 m/s; (b) 0 g/L, total burning rate, 19.5 m/s. Time is measured from the moment of foam ignition. Instantaneous values of flame speed are presented for each time instant.

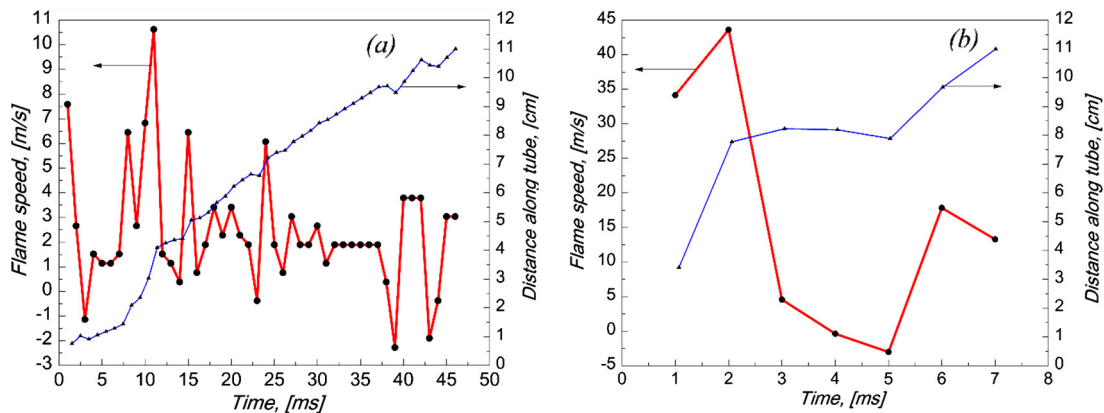


Fig. 11. Plots of the flame speed and distance traveled vs. time: (a) combustible foam composition corresponds to Fig. 4b, total burning rate, 2.6 m/s; (b) combustible foam composition corresponds to Fig. 4a, total burning rate, 15.7 m/s.

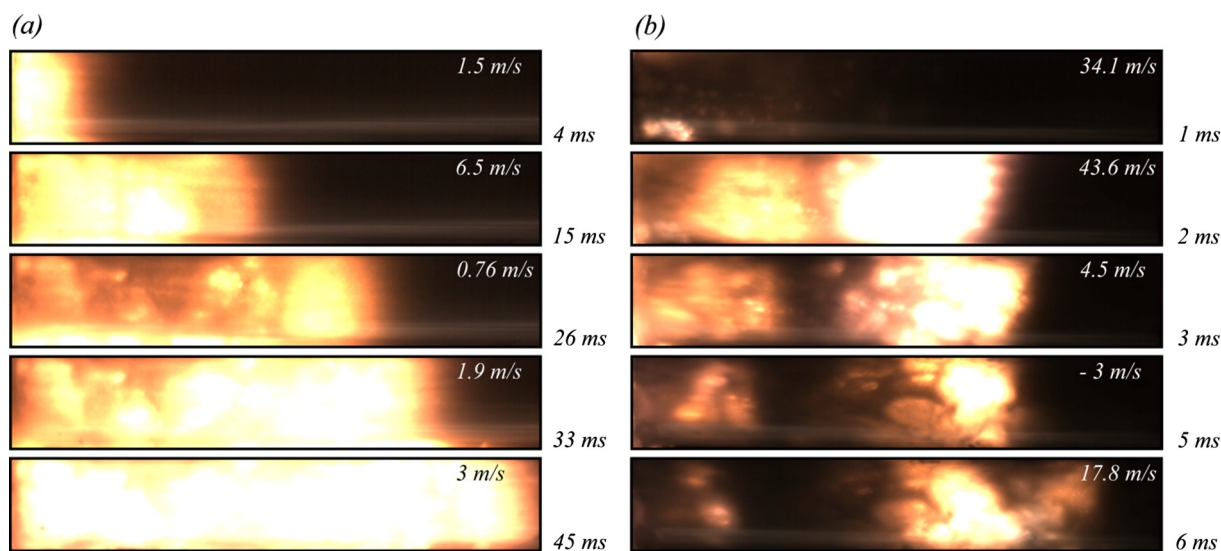


Fig. 12. Structure of combustion zone: (a) combustible foam composition corresponds to Fig. 4b, total burning rate, 2.6 m/s; (b) combustible foam composition corresponds to Fig. 4a, total burning rate, 15.7 m/s. Time is measured from the moment of foam ignition. Instantaneous values of flame speed are presented for each time instant.

with water vapors. Indeed the comparison between the photographs of flame structures in sulfonol- and detergent-containing foams shows that the flame thickness in the first case occurs to be smaller than in the second one (compare Fig. 12a and b).

4. Conclusion

The paper studies experimentally and analyzes both problems of combustion and problems of stability of foamed emulsions. Combustible foamed emulsion is prepared by the chemical method of foaming with the use of heptane or o-xylene and water solution of surfactant. One can distinguish two basic regimes of foamed emulsion combustion: oscillating and accelerated regimes of flame propagation. Flame acceleration is determined by explosive boiling of liquid phase. Flame speed oscillations are determined by the incomplete fuel drops evaporation in the convective-diffusion zone of flame. Dependence of total burning rate on the heptane volume fraction has a maximum. The use of MgO particles favors the increase in total burning rate of the foam. MgO particles determine foam destabilization via the decrease in stabilizer concentration due to its adsorption on the particles surface. When changing the stabilizer of mixed type with the anionic stabilizer at fixed other conditions the stability of combustible foam decreases while the flame speed increases. Foamed emulsion represents a unique example of combustible system which opens new opportunities of direct utilization of water-saturated oils as fuels avoiding the stage of components separation.

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