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Research article

Effect of ultrasonic emulsification on the combustion of foamed emulsions

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ABSTRACT

The paper analyzes the combustion process of foamed emulsion on the basis of experimental research and phenomenological representations. The foamed emulsion represents a multiphase system consisting of oxygen bubbles dispersed in the oil-in-water emulsion. The research interest to such combustible systems is determined primarily by the fact that even at significant water content the foamed emulsion preserves its combustibility. This paper is mainly focused on the analysis of emulsion preparation methods (mechanical agitation or ultrasonic emulsification) and their influence on the foamed emulsion combustion. It is obtained that ultrasonic emulsification favors decrease in total burning rate of the foam and narrowing in concentration limits of flame propagation. An important role in flame acceleration in the foam belongs to the processes related with explosive boiling of liquid phase of the foam wherein oil drops could play a role of heterogeneous centers of nucleation for vapor bubbles. It is shown that if ultrasonic emulsification causes decrease in the sizes of oil drops in the emulsion below a certain critical value then the conditions for successive flame acceleration will be degenerated.

1. Introduction

An important issue for contemporary thermal power engineering is the decrease in the emission of harmful pollutants when burning hydrocarbon fuels. One of the perspective ways to solve this problem is the use of water as a part of hydrocarbon fuel [1–8]. Water favors the decrease in flame temperature and due to this NO_x emission can be significantly reduced [9–12]. In addition the use of water could lead to the changes in rheological properties of the fuel that in turn favors the quality of its spraying [13].

A perspective direction of contemporary research is the analysis of opportunity to use emulsive fuel (oil-in-water and water-in-oil) inside diesel engines [14–18]. At certain conditions the combustion of emulsion drops inside engine combustor could be accompanied with rather important from applied point of view phenomenon of microexplosion [19–24]. The essence of this phenomenon is the explosive boiling of emulsion drops that leads to the formation of an array of small enough fuel droplets. Due to the increase in contact surface between reacting components the burning efficiency increases. Combustion mechanism of emulsion drops depends significantly on their structure (on number density and diameter of disperse phase droplets and on diameter of emulsion drop as a whole) [23,25]. Structure of emulsion drops determines both the overall characteristics of diesel engine [26] and the concentration of formed pollutants [27,28].

By varying the structural parameters of emulsive fuel one is able to change its properties significantly. On the basis of such a kind of results recently in [29–32] we proposed a new type of emulsive fuel – a foamed emulsion. Foamed emulsion represents a multiphase system consisting of gaseous bubbles dispersed in the emulsion. Due to its wide spread in our everyday life this class of foams attracted to itself a wide research interest [33,34]. Combustible foamed emulsion consists of oxygen bubbles in the emulsion which in turn represents a water solution of stabilizer with hydrocarbon drops dispersed in it. The research interest to the combustible foamed emulsions is driven by a set of reasons. First of all 80% of worldwide crude oil is produced in the form of oil-in-water emulsion and in set of cases the problem arises concerning direct burning of oil-in-water blend without stage of components refining. While solving this problem a foamed emulsion can be utilized due to its intrinsic features. For example, foamed emulsion containing 90 wt% of water still preserves its combustibility [30]. Foamed emulsion can be also utilized as a fuel for microscale power devices [35]. Sometimes when elaborating such devices the problems arise related with development of miniature systems for fuel spraying. When utilizing the foamed emulsion as a fuel this problem does not arise since the foam decays into the drops by itself in the process of combustion. Significant disadvantage of the foamed emulsion is its intrinsic tendency to shrinkage [34]. Therefore one should utilize the combustible foam immediately after its preparation.

One of the possible variants of continuously operating burner for foamed emulsion burning is presented in Fig. 1. Such a device consists of three main parts: unit for emulsion preparation, foam generator and combustor. Oil-in-water emulsion is prepared inside a reactor by

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Nomenclature

MA	mechanical agitation
UE	ultrasonic emulsification
B	bridging coefficient, N^2/m^2
D	diameter of impeller, m
$D(3,2)$	average diameter of drops in the emulsion, m
$D(4,3)$	average diameter of drops in the emulsion, m
d_i	diameter of *i*-th drop in the emulsion, m
E	entry coefficient, Nm^{-1}
h	height of impeller, m
L_w	latent heat of vaporization for water, J/kg
N_n	number density of nucleation centers, m^{-3}
n_i	number of *i*-th droplets in the emulsion
P	pressure, Pa
ΔP	pressure difference between vapor in bubble and surrounding medium at the moment of explosive boiling of liquid, Pa
R_b	radius of vapor bubble, m
r_{cr}	radius of critical bubble, m
r_d	average radius of emulsion drop, m
r_g	average radius of gaseous bubbles in the foam, m
r_{max}	maximal radius of oil drop in the emulsion, m
r_o	average radius of oil drops, m
r_w	average radius of water drops, m
S	flame speed in the foam, m/s
S_b	total burning rate, m/s
S_{b*}	limit flame speed, m/s
$S_{b(n)}$	total burning rate at time instant t_n, m/s
S_{bmin}	minimal flame speed corresponding to the explosive boiling, m/s
$\widetilde{S}_b$	maximal total burning rate of foam corresponding to complete evaporation of fuel drops, m/s
T_s	saturation temperature, K
ΔT	liquid superheat relative to saturation temperature, Pa
ΔT_b	difference between flame front temperature and initial foam temperature, K
ΔT_{ex}	liquid superheat at the moment of its explosive boiling, K
t	time, s
β	coefficient, $m^{2/3}s^{1/3}$
γ	coefficient, $m^{4/3}/s^{1/3}$
ε	dissipation of turbulent energy, m^5/s^3
λ_l	thermal conductivity of liquid, W/mK
ν	kinematic viscosity of water, m^2/s
ρ_w	water density, kg/m^3
ρ_v	water vapor density, kg/m^3
$\sigma_{w/o}$	oil/water interfacial tension, N/m
σ_o	surface tension of the oil phase, N/m
σ_w	surface tension of the aqueous phase, N/m
τ_d	characteristic hydrodynamic time of foam decay, s
τ_{ex}	characteristic time of explosive boiling, s
φ_{ex}	critical vapor content at the moment of explosive boiling of liquid
φ_f	volumetric content of oil phase in the emulsion
$\overline{\varphi}_f$	critical volumetric content of oil phase in the emulsion
χ_f	thermal diffusivity of foam, m^2/s
χ_l	thermal diffusivity of liquid, m^2/s
ω	velocity of reacting mixture ejection, m/s
ω_b	rotation speed of the stirrer, s^{-1}

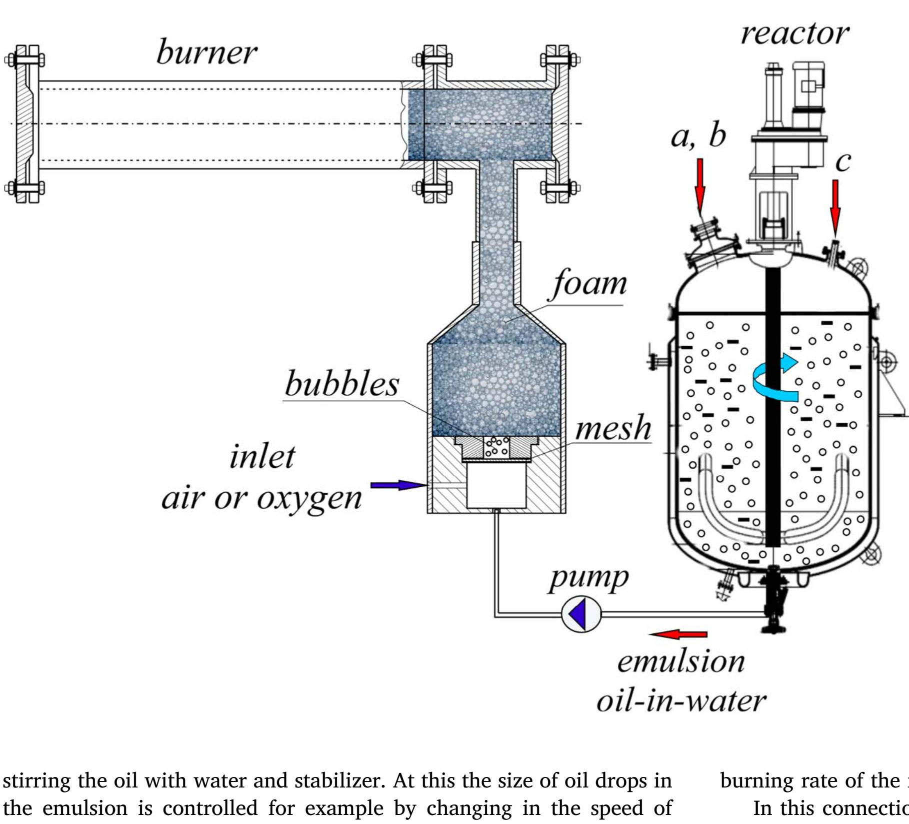

Fig. 1. Schematic representation of the device for production of foamed emulsion and its burning. The reactor is fed with initial components: *a* – water; *b* – oil; *c* – stabilizer.

stirring the oil with water and stabilizer. At this the size of oil drops in the emulsion is controlled for example by changing in the speed of blender. With the use of pump the emulsion fed into the foam generator where it is foaming by dispersing of air or oxygen in it. After this the foam burns inside combustor. An important question arising when elaborating such devices concerns adjustment between the total burning rate of the foam and the rate of foam generation.

In this connection the problem arises concerning the regulation of flame speed in the foam. One can distinguish several regimes of foamed emulsion combustion, and the flame speed could differ significantly depending on the realized regime. Along with slow flame propagation regime the combustion of foamed emulsion can proceed in oscillating or