



## Full Length Article

## Combustion of the foamed emulsion containing biochar microparticles

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## ABSTRACT

Foamed emulsion containing biochar particles can serve as a perspective type of fuel for contemporary power engineering. Such a combustible system represents a multiphase system consisting of oxygen bubbles dispersed in the oil-in-water emulsion which in turn contains biochar microparticles. The paper considers the issues related with combustion of foamed emulsion containing biochar particles. In the process of experimental study we determined the dependencies of flame speed in the foamed emulsion on the concentration of biochar microparticles for different types of aliphatic hydrocarbons (hexane, heptane, isooctane and nonane). It is found that the use of biochar microparticles could lead to rather significant increase in total burning rate of the foamed emulsion. Thus, for example, the addition of biochar particles into the isooctane-based foam leads to the four-times increase in total burning rate. Herewith, the dependence of total burning rate of the foam on the biochar particles concentration is non-monotonic, so the maximum burning rate is achieved at some moderate biochar particles concentration. With the help of laser-lighted photography of multiphase flow the experimental data is obtained for the diameter of water droplets forming in the process of foamed emulsion decay during its combustion. It is obtained that biochar particles favor finer dispersing of liquid phase of the foam since they represent by themselves heterogeneous centers of vapor bubbles nucleation. In turn the diameter of water droplets defines the heat losses from the flame front and therefore the flame speed. On the basis of simple phenomenological representations we obtained the estimate for flame speed in the foamed emulsion containing biochar microparticles. Obtained relations makes it possible to substantiate the non-monotonic manner the total burning rate depends on the biochar microparticles content in the emulsion.

## 1. Introduction

Important issues for contemporary power engineering concern the problems of utilization of the water-saturated oils [1] and the renewable types of fuels [2–4]. For example, one is able to improve significantly the quality of diesel fuel spraying in the engine due to the water addition to the fuel [1] as well as to reduce emission of  $NO_x$  and particular matter. An important field of contemporary research is the analysis of opportunity to utilize combustible solid particles as a component of liquid fuel [5–7]. Such a type of fuel can possess a set of significant advantages. For example, Feng and Wu [8] demonstrated that heterogeneous fuel (bio-oil/biochar) offers a series of advantages including high energy density and low production cost. At the same time it should be noted that the utilization of biochar particles as a part of liquid fuel can favor the increase in particulate matter emission [8] and the increase in ignition temperature of slurry fuel [9]. The serious problem related with biomass combustion is the formation of a large amount of solid products which favor the phenomena of deposition and corrosion [10].

One of the possible paths aimed to solve these problems could be provided by utilization of the foamed emulsion, containing biochar particles, as a fuel. Such a multiphase combustible system consists of oxygen bubbles dispersed in the water solution of stabilizer which in turn contains oil drops and biochar particles.

The research interest to the combustion of foamed emulsions [11–15] is due to the fact that they possess a set of unique properties. For example, at certain conditions the foamed emulsion containing about 90 wt% of water is able to preserve its combustibility [11,13]. Moreover, the technological process of combustible foamed emulsion preparation is rather simple. At the first stage the emulsion is prepared via stirring the oil with water solution of stabilizer. Farther, the emulsion is foamed with help of air or oxygen dispersion in it (Fig. 1). An important advantage of foamed emulsion is the fact that the flame speed could be regulated in rather wide range. For example, this can be achieved with the use of negligible amounts of magnesium oxide microparticles. In this particular case the total burning rate of the foam can be increased several times [13].

Scheme of industrial facility for preparation and burning of the

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**Nomenclature***Latin*

$B$	bridging coefficient, $\text{N}^2\cdot\text{m}^{-2}$
$B_w$	transfer number, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$c$	heat capacity of gas-drop mixture, –
$c_l$	heat capacity of liquid, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$D$	tube diameter, m
$E$	entry coefficient, $\text{N}\cdot\text{m}^{-1}$
$E_a$	effective activation energy, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$f_w$	defined by Eq. (12), –
$G_w$	rate of water drop evaporation, $\text{kg}\cdot\text{s}^{-1}$
$J_c$	mass burning rate of biochar particle, $\text{kg}\cdot\text{s}^{-1}$
$L_w$	latent heat of vaporization for water, $\text{J}\cdot\text{kg}^{-1}$
$l$	characteristic distance of reacting mixture ejecting, m
$N_b$	number of bubbles per unit volume of liquid, $\text{m}^{-3}$
$N_c$	number density of biochar particles per unit volume of the foam, $\text{m}^{-3}$
$\bar{N}_c$	number density of biochar particles corresponding to the total burning rate maximum, $\text{m}^{-3}$
$\tilde{N}_c$	number density of biochar particles corresponding to the total burning rate minimum, $\text{m}^{-3}$
$N_w$	number of water drops per unit volume, $\text{m}^{-3}$
$\Delta P$	pressure difference between vapor in bubble and surrounding medium at the moment of explosive boiling of liquid, Pa
$\gamma$	defined by Eq. (13), $\text{W}\cdot\text{m}$
$\lambda$	thermal conductivity coefficient of the gas, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
$\lambda_l$	thermal conductivity of liquid, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$
$\vartheta$	defined by Eq. (16), K
$\mu_f$	effective viscosity of the foam, $\text{Pa}\cdot\text{s}^{-1}$
$\rho$	gas-drop mixture density, $\text{kg}\cdot\text{m}^{-3}$
$\rho_l$	liquid density, $\text{kg}\cdot\text{m}^{-3}$
$\rho_v$	water vapor density, $\text{kg}\cdot\text{m}^{-3}$
$Q$	chemical energy release, $\text{J}\cdot\text{kg}^{-1}$
$Q_c$	calorific effect of biochar, $\text{J}\cdot\text{kg}^{-1}$
$q$	heat losses from the flame front, $\text{W}\cdot\text{m}^{-2}$

$R$	universal gas constant, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$
$R_b$	radius of vapor bubble, m
$r_w$	average water drop radius, m
$r_o$	average oil drop radius, m
$S$	flame speed in foam, $\text{m}\cdot\text{s}^{-1}$
$S_b$	total burning rate, $\text{m}\cdot\text{s}^{-1}$
$S_L$	laminar burning velocity relative to unburned mixture, $\text{m}\cdot\text{s}^{-1}$
$T$	temperature, K
$T_0$	initial temperature, K
$T_b$	maximum flame temperature, K
$T_b'$	temperature on the flame front, K
$T_s$	saturation temperature, K
$\Delta T_b$	difference between temperature of the flame front and initial foam temperature, K
$\Delta T_l$	liquid overheating relative to saturation temperature, K
$\Delta T_{ex}$	liquid overheating at the moment of its explosive boiling, K
$t$	time, s
$v$	velocity of reacting mixture ejection, $\text{m}\cdot\text{s}^{-1}$
$x$	distance, m
$Y_f$	initial concentration of oil, –
$Z$	pre-exponential term in the Arrhenius expression, $\text{s}^{-1}$

*Greek*

$\alpha$	defined by Eq. (8), $\text{m}\cdot\text{s}^{-1}\cdot\text{K}^{-1/2}$
$\beta$	defined by Eq. (13), $\text{W}\cdot\text{m}^{-2}$
$\sigma_o$	surface tension of the oil phase, $\text{N}\cdot\text{m}^{-1}$
$\sigma_{ow}$	oil/water interfacial tension, $\text{N}\cdot\text{m}^{-1}$
$\sigma_w$	surface tension of the aqueous phase, $\text{N}\cdot\text{m}^{-1}$
$\tau$	time of reacting mixture ejection, s
$\varphi_w$	volume content of water in the foam, –
$\chi_l$	thermal diffusivity of liquid, $\text{m}^2\cdot\text{s}^{-1}$
$\psi_{ex}$	critical vapor content at the moment of explosive boiling of liquid, –
$\omega$	vapor velocity, $\text{m}\cdot\text{s}^{-1}$

foamed emulsion containing biochar particles is presented in Fig. 1. It consists of two main units – reactor and burner. Reactor for emulsion preparation represents a vessel equipped with stirrer. The reactor is fed with oil, water, surfactant and biochar microparticles. The oil-in-water emulsion with given size of oil droplets is prepared via choosing the speed of rotation of stirrer. After, the emulsion-suspension blend is supplied to the burner using the pump. With the help of porous element

in the bottom part of the burner the dispersion of oxygen bubbles is carried out. Finally, the prepared foam is burned down in the burner.

In many ways, the problem of studying the combustion of foamed emulsion with biochar particles is ideologically close to the issues of oxy-coal combustion [16–19], emulsion drops combustion [20], emulsion-suspension drops combustion [21], suspension drops combustion [22,23] and char particles combustion [24]. Herewith, it should be noted that the mechanism of foamed emulsion combustion possesses pronounced individual features which first of all are related with the process of foam decay during the flame propagation.

This paper analyzes the combustion of foamed emulsion containing biochar microparticles on the basis of experimental study. Experimental results show that even negligible change in the biochar particles content in the foam could lead to the significant change in total burning rate of the foamed emulsion. Simple phenomenological estimations are deduced that can be used to substantiate the effect of biochar particles on the flame speed in the foam.

## 2. Experimental section

### 2.1. Foamed emulsion preparation

To prepare the combustible foam the following aliphatic hydrocarbons were used: hexane, heptane, iso-octane and nonane. Their boiling temperatures at atmospheric pressure are correspondingly:

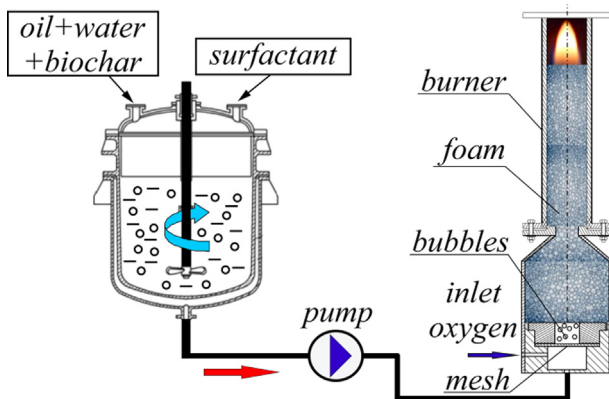


Fig. 1. Scheme of industrial setup for preparation and burning of the foamed emulsion-suspension blend.

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