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Intensities of microexplosive fragmentation of two-liquid droplets

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The paper presents the results of experimental study of intense fragmentation of two-liquid droplets of the core/shell type (water/flammable liquid) during heating in a high-temperature medium. Water concentration in the two-liquid droplets was 10 ± 2 vol.%. Ranges of variation in fragmentation intensities in the puffing and microexplosion modes proved to be $< 150\,\mathrm{s}^{-1}$ and $> 500\,\mathrm{s}^{-1}$, respectively. The study has shown that, as the gas medium temperature increases in the range of 600 ± 10 to 750 ± 10 K, the microexplosion fragmentation intensities increase more than 5 times in the case of isolated two-liquid water/rapeseed oil droplets, 1.5 times in the case of water/diesel fuel droplets, and 2.4 times in the case of water/kerosene droplets.

Keywords: fragmentation intensity, puffing, microexplosion, two-liquid droplet, rapeseed oil, kerosene.

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Tightening the requirements for reducing pollutant emissions from the combustion of liquid hydrocarbon fuels, as well as growth of relevant penalties, motivates development of new techniques for controlling burning in combustion chambers of propulsion and power plants. Integral characteristics of such devices and efficiency of combustion as a whole are governed by the processes of fuel atomization and mixing of the air-fuel mixture components [1,2]. To intensify the processes of mixing, it is necessary to provide thermal conditions promoting multiple crushing of the fuel-composition droplets with forming small secondary fragments. A promising technique for managing atomization of fuel compounds is secondary fragmentation of the liquid droplets in multiphase and multicomponent flows [3]. The processes of secondary fragmentation promote a several-fold increase in the area of the liquid evaporation surface due to rapid fragmentation of initial droplets down to several tens of micrometers [4]. As a result of intense heating and local overheating of low-boiling components contained in multiphase and multicomponent droplets, puffing and microexplosion modes get realized [5]. To separate the microexplosive fragmentation modes into microexplosion and puffing, a visual criterion based on the number and size of secondary fragments is typically used. Puffing is understood as partial disintegration of the initial droplet, during which the secondary liquid fragments are formed in the quantity of up to 20 with the sizes (radii) of more than 0.3 mm; microexplosion is complete disintegration of the initial droplet with formation of fine aerosol [6]. Based on the fragmentation intensity, it is possible to characterize the dispersed liquid volume and time during which the initial droplet gets disintegrated [7]. There are known several approaches to determining the fragmentation intensity for heterogeneous droplets. As a rule, they involve accounting for variations in the droplet volume [7] and size [8]. The criterion for the transition between the puffing and microexplosion modes (in terms of fragmentation intensity and their variation ranges) play an important role in organizing primary atomization of liquids and providing efficient conditions for the secondary disintegration of droplets. At present, the literature presents a limited number of results on the intensities of microexplosive fragmentation and criteria of decay, most of which concern studying these processes during heating of mixed fuels based on biodiesel, 1-pentanol, methanol and hexadecane [7,8]. At the same time, no substantiated method for separating the droplet puffing and microexplosion modes has been developed. Just these tasks have motivated this study.

The experimental procedure and bench layout (Fig. 1) are similar to those used in [4]. As the heating system, a tubular muffle furnace was used (with the heating temperature range of up to 1573 K), which was arranged upright to the bench base. A thermally insulated metal cylinder designed to keep constant the muffle furnace outlet temperature was mounted above the muffle furnace outlet. The cylinder had holes for injecting droplets into the heating zone, recording the fragmentation processes, and illuminating the droplets with a LED spotlight. The two-liquid droplets under study were injected into the measurement area by using the coordinate mechanism to the end of which a holder made from thin nichrome wire 0.2 mm in diameter was attached. Temperature of the air-gas medium was measured by a system consisting of a National Instruments data acquisition complex and low-inertia thermocouples with the error not higher than 3 K and inertia of less than 0.1 s. The furnace temperature was varied in the range of 1073 to 1273 K, which ensured the heating-zone gas temperature variation from 600 to 750 K. The temperature range was selected based on the fact that the limiting conditions for realizing microexplosion and puffing modes get achieved at the appropriate heat exchange [9]. This enabled establishing the ranges of microexplosive decay

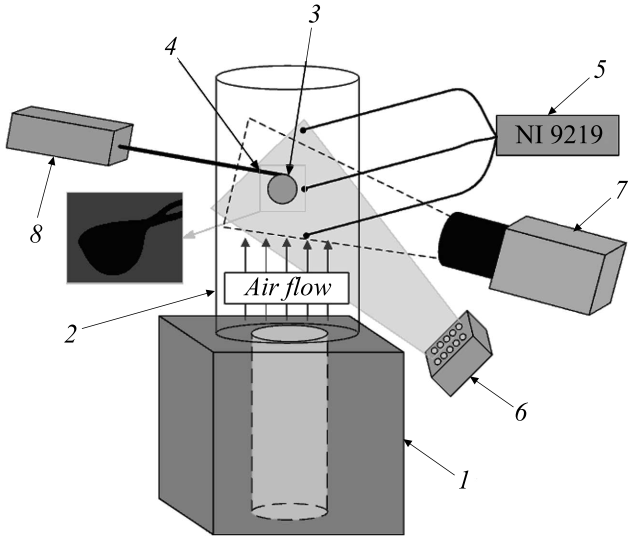

Figure 1. A test bench for measuring fragmentation characteristics of two-liquid droplets. *1* — tubular muffle furnace, *2* — thermally insulated cylinder, *3* — two-liquid droplet, *4* — holder, *it 5* — temperature recording system (National Instruments), *6* — light source, *7* — high-speed video camera, *8* — coordinate mechanism.

intensities in different modes. The processes of heating, evaporation and fragmentation of droplets were recorded with a high-speed video camera. The recording frequency during the experiments was 10^4 pps at the 768×768 px resolution. Video fragments were processed using the authorś software code [10]. During heating and fragmentation, initial droplet radii R_d were measured, as well as durations of microexplosive fragmentation τ_s. Systematic errors in determining R_d and τ_s were 0.0125 mm and 0.1 ms, respectively. To minimize random errors in measuring those parameters, a series of 15–20 experiments was performed under identical initial conditions.

The liquids under study were distilled water, kerosene TS-1, diesel fuel and rapeseed oil. The technique for generating two-liquid droplets was similar to that used in [9]. Water concentration during the experiments was assumed to be 10 vol.%. This concentration enabled achieving the maximum increase in the evaporation surface area after fragmentation [9]. In the experiments, the initial droplet radii were 0.9 mm. The Table presents the properties of liquids used in the experiments; the values were obtained in the studies performed in [11].

Fig. 2 presents typical video frames illustrating fragmentation of two-liquid droplets with initial radius $R_{d0} = 0.9$ mm at gas temperature $T_a = 750$ K. Transitions between the modes of partial fragmentation (puffing) and complete fragmentation (microexplosion) were detected over the entire range of studied temperatures at all the compositions. The obtained video frames show that fragmentation of two-liquid droplets in the microexplosion mode is more intense for diesel fuel and rapeseed oil than for kerosene-based droplets. In [4] there was revealed that microexplosive fragmentation proceeds with formation of the maximum number of secondary fragments in the case when the fuel shell is represented by highly viscous liquids. In this case, the pressure pulse from arising vapor bubbles does not induce separation of isolated secondary fragments of liquid from the parent droplet bulk due to a high internal friction force, but an intense microexplosion takes place.

The most preferable approach for determining the fragmentation efficiency is that presented in [7]. This approach enables calculation of the fragmentation intensity for all cases, including that when the two-liquid droplet under study gets fragmented with formation of a difficult-to-detect fine aerosol. To assess the intensity of fragmentation of two-liquid droplets in the puffing and microexplosion modes, the expression from [7] is used:

$$I_i = \frac{V_{0i} - V_{1i}}{\tau_s V_{0i}} \, [\mathrm{s}^{-1}],$$

where τ_s is the duration of the two-liquid droplet fragmentation [s], V_{0i} and V_{1i} are the liquid volumes before and after fragmentation [m^3].

The volumes of liquid were calculated based on analyzing the droplet shadow images by using the author's software code [10]. Droplet radius R_d was calculated as a radius of circle having the same area as the region occupied by the droplet in the image. Then, the droplet volume was calculated as the sphere volume $V = 4\pi R_d/3$. Experiments aimed at analyzing errors in determining droplet volumes included extra procedures in the course of which rapeseed oil droplets of a given volume ($2.5\,\mu$l) were placed with an electronic dispenser onto a room-temperature holder [9]. Sizes of the droplets presented in the obtained video frames were fixed, and their volumes were calculated via the algorithm given in [10]. The results obtained were then compared with the expected value $2.5\,\mu$l. Volumes of 30 droplets were assessed under identical conditions. The analysis showed that the average calculated droplet volume was $2.43\,\mu$l, while the relative volume-measurement error was 2.8%.

An important aspect in analyzing the microexplosive decay intensities is the video-recording speed. In this work, the recording frequency was 10^4 pps. If the initial droplet was completely destroyed in one frame, the minimum time interval during which the process of decay was observed could be $1/10^4$ s. The maximum detectable decay intensity could not exceed $10^4\,\mathrm{s}^{-1}$. Faster recording devices may help refining the values of secondary fragmentation intensities. In our experiments, maximum detected intensities did not exceed $5000\,\mathrm{s}^{-1}$.

Fig. 3, *a* presents the calculations of fragmentation intensities I for two-liquid droplets in the puffing and microexplosion modes with varying the gas medium temperature. In the puffing mode, parameter I values did not exceed $150\,\mathrm{s}^{-1}$, while those in the microexplosion mode were higher than $500\,\mathrm{s}^{-1}$. The established variation

Main properties of the liquids used in the study at 300 K [11]

Parameter	Distilled water	Rapseed oil	Diesel fuel	Kerosene
Density, kg/m^3	1010	870	860	727
Heat capacity, J/(kg·K)	4200	2352	2250	1802
Thermal conductivity, W/(m·K)	0.61	0.17	0.12	0.1
Dynamic viscosity, mPa·s	1	34	2.7	2.4
Surface tension, N/m	0.072	0.034	0.025	0.024

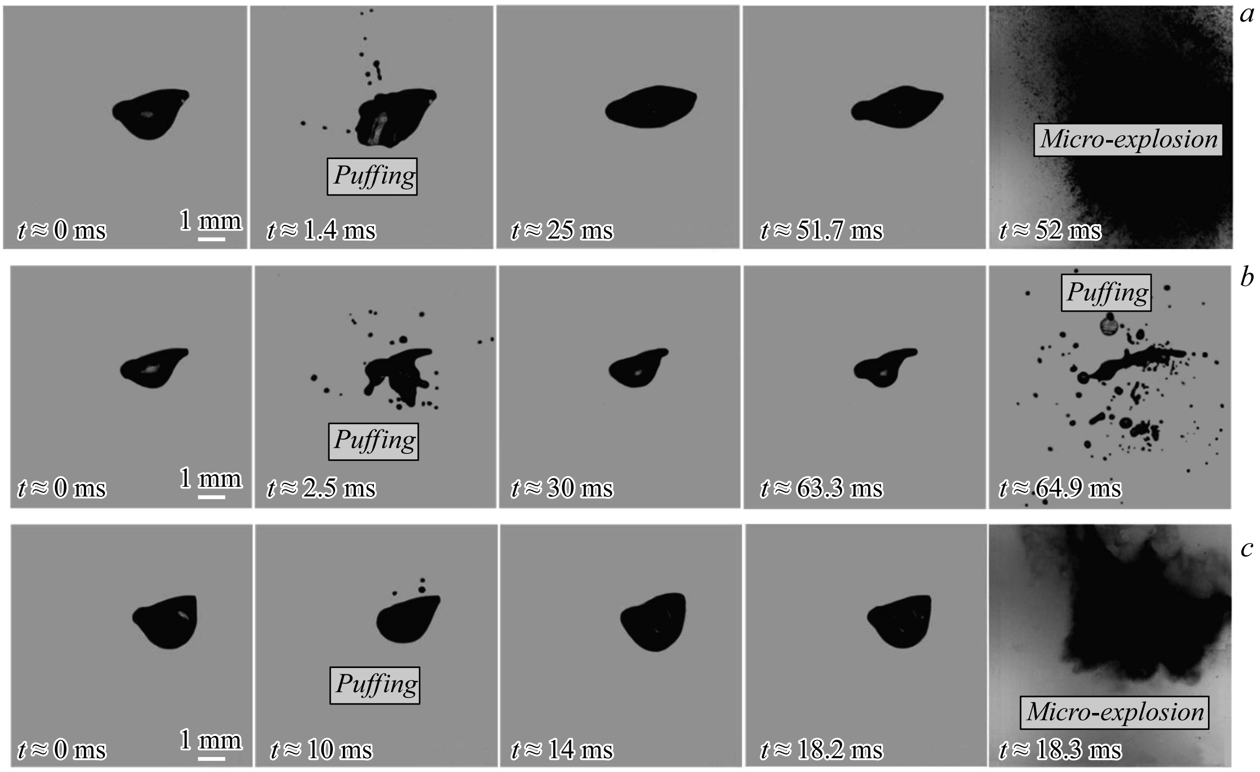

Figure 2. Video frames of two-liquid droplet fragmentation in the puffing and microexplosion modes ($R_{d0} = 0.90 \pm 0.05$ mm, $T_a = 750 \pm 10$ K). *a* — diesel fuel 90 vol.%, water 10 vol.%; *b* — kerosene 90 vol.%, water 10 vol.%; *c* — rapeseed oil 90 vol.%, water 10 vol.%.

ranges of I allow independent highaccuracy identification of the droplet fragmentation mode at any input parameters of the experiments. Over the entire range of studied temperatures, the maximum intensities were fixed for droplets based on diesel fuel, while the minimum ones were observed for kerosenebased droplets. Fig. 3, *a* shows that the fragmentation intensities of two-liquid droplets in the puffing and microexplosion modes increase with the gas medium temperature increasing from 600 to 750 K, which is caused by an increase in the water heating rate and achievable degrees of its overheating [12]. The maximum increase in the fragmentation intensity (by a factor of 5) was fixed for two-liquid droplets based on rapeseed oil, while the minimum one (by a factor of 1.5) was fixed for droplets based on diesel fuel in the microexplosion mode. As the temperature increased, the fragmentation intensity of diesel-fuel-based droplets remained maximum, but no significant variations were observed.

An increase in viscosity of the liquid fuel that forms a shell of the two-component droplet leads to an increase in the energy needed for formation and growth of a vapor bubble inside it. Fig. 3, *b* presents the intensities of two-liquid droplets fragmentation in the puffing and microexplosion modes versus the Ohnesorge number (Oh). The higher is the Ohnesorge number, i. e. the higher is the fuel cladding viscosity, the more difficult is achieving the critical conditions for the droplet fragmentation in a short time interval. As the gas medium temperature increases, viscosity and surface tension of liquid fuels decrease. This results in an increase in the fragmentation intensity.

Analysis of Fig. 3, *b* shows that, despite the properties of diesel fuel and kerosene are comparable, fragmentation

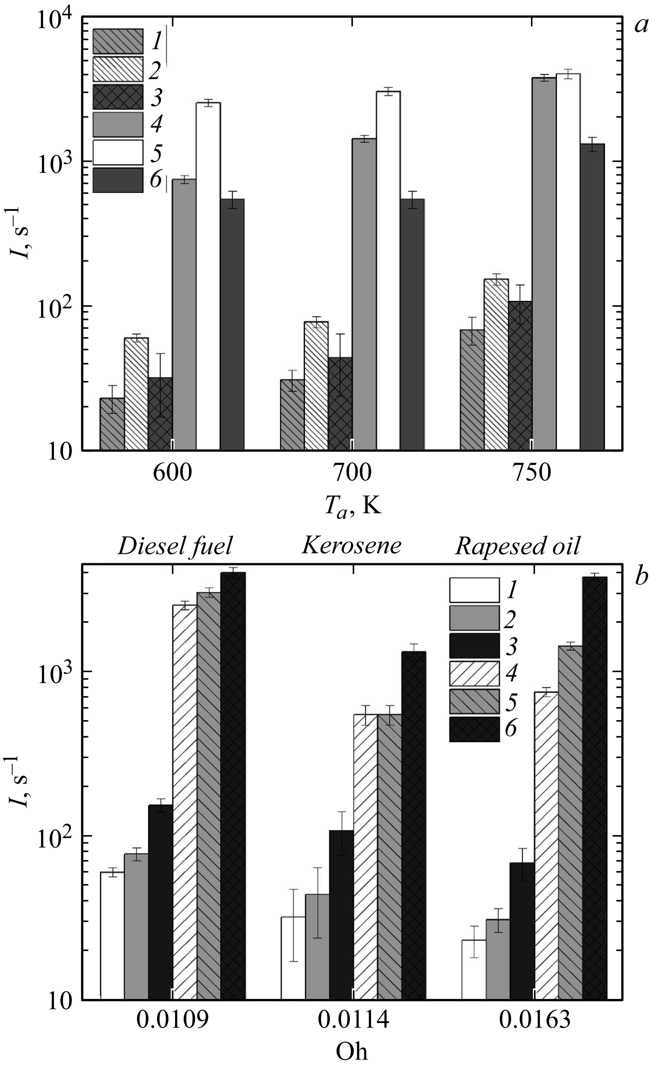

Figure 3. Intensities of the two-liquid droplet fragmentation. *a* — in the case of varying the gas temperature: *1* — puffing, rapeseed oil 90 vol.%, water 10 vol.%; *2* — puffing, diesel fuel 90 vol.%, water 10 vol.%; *3* — puffing, kerosene 90 vol.%, water 10 vol.%; *4* — microexplosion, rapeseed oil 90 vol.%, water 10 vol.%; *5* — micro-explosion, diesel fuel 90 vol.%, water 10 vol.%; *6* — micro-explosion, kerosene 90 vol.%, water 10 vol.%. *b* — in the case of varying the type of liquid fuel: *1* — puffing, $T_a = 600 \pm 10$ K; *2* — puffing, $T_a = 700 \pm 10$ K; *3* — puffing, $T_a = 750 \pm 10$ K; *4* — microexplosion, $T_a = 600 \pm 10$ K; *5* — microexplosion, $T_a = 700 \pm 10$ K; *6* — micro-explosion, $T_a = 750 \pm 10$ K.

intensity of the latter is lower. This is due to two reasons. First, kerosene has lower viscosity and surface tension. Hence, its fragmentation takes less energy. Second, the kerosene evaporation rate is significantly higher (more than 2 times) than that of other liquids under study (diesel fuel and rapeseed oil) [10]. This results in that, as the droplet is being heated, the ratio of concentrations of the liquids contained in it varies significantly. Hence, the fragmentation is less efficient, large secondary fragments are formed. Due to intense evaporation of kerosene, a part of the supplied energy is spent also on the phase transition, which reduces the dispersed phase heating rate [12].

The experiments performed in this study revealed the differences in intensities of two-liquid droplet fragmentation in the puffing and microexplosion modes. It has been shown that, as the gas medium temperature increases, fragmentation intensities in the puffing and microexplosion modes increase several times. In the puffing mode, fragmentation intensities did not exceed $150\,\mathrm{s}^{-1}$, while those in the microexplosion mode were higher than $500\,\mathrm{s}^{-1}$. Maximum fragmentation intensities were exhibited by diesel-fuel-based droplets in the microexplosion mode ($I = 4000\,\mathrm{s}^{-1}$), while minimum ones corresponded to rapeseed-oil-based droplets in the puffing mode ($I = 25\,\mathrm{s}^{-1}$). The proposed approach allows predicting reasonable conditions for crushing droplets of different compositions taking into account the restrictions on relevant resources in the group of applications, for instance, in crushing droplets of fuels, fire extinguishing fluids, petrochemical reagents, purified liquids, etc. Depending on requirements for the design of combustion chambers and mixing reactors, it is possible to predict the ranges of the heating temperatures reduction and possible energy savings based on the established values of fragmentation intensity.

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Conflict of interests

The authors declare that they have no conflict of interests.

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