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Micro-explosive fragmentation of two-fluid droplets based on tall oil

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The paper presents the results of experimental study of the micro-explosive fragmentation of two-liquid drops during heating in a high-temperature medium. The characteristics of secondary fragments during micro-explosive fragmentation of single droplets based on tall oil were studied. With micro-explosive fragmentation of droplets based on crude tall oil, it is possible to increase the evaporation surface area by more than 70 times. It has been established that during the secondary grinding of drops based on crude tall oil due to micro-explosive effects, it is possible to obtain 2−3 times more secondary fragments than when fragmenting drops based on kerosene and filtered tall oil under identical heating conditions

Keywords: micro explosion, fragmentation, secondary fragments, biofuels, tall oil.

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Mounting environmental challenges spur the interest in application of biofuels based on vegetable oils in the energy industry and the transport sector. The use of biofuels as alternatives to traditional fossil fuels provides a way to cut efficiently the emission of carbon, nitrogen, and sulfur oxides [1]. A large-scale transition to renewable fuels (specifically, vegetable-based fuel) is one of the most promising strategies for reduction of anthropogenic emissions in certain branches of industry. Methods for production of such alternative fuels as biodiesel, biokerosene, bioethanol, and biogasoline are applied [2,3]. Crude tall oil is the primary by-product of manufacture of pulp from coniferous wood; it is a dark brown fluid with an odor similar to the one of tree resin [4]. Since crude tall oil is rather cheap, its use as a raw material for biofuel production is economically and ecologically viable [2,5]. The efficiency of biofuel production may be raised through the application of micro-explosive atomization of two-fluid droplets. These processes allow one to increase manyfold the evaporation and chemical-reaction surface area of a fluid in the course of atomization of the initial droplets into fragments several tens of micrometer in size [6,7]. Applying these effects, one may intensify the process of biogas production from tall oil. An important task in the study of regularities of micro-explosive breakup is to examine the results of atomization of droplets of multicomponent fuel (e.g., the size of secondary fragments and an aerosol cloud filled by them). Having determined the required conditions for production of secondary fragments of a certain size, one may optimize the operating modes of processing equipment, minimize the fuel consumption, reduce anthropogenic emissions, and stabilize the sputtering process. It is imperative in this context to determine the characteristics of secondary fragments for compositions based on tall oil. These challenges were the motivation behind the present study.

A tube muffle furnace was used as a heating system in experiments (the temperature range was 300–1573 K). A metallic thermally insulated cylinder was mounted on top of the muffle furnace to maintain a constant temperature at the furnace outlet. Orifices made in the cylinder were used to introduce droplets into the heating zone, record the breakup processes, and illuminate the droplets by a LED spotlight. The droplets under study were introduced into the recording area using a coordinate mechanism with a holder (with nichrome wire 0.2 mm in diameter) at the end of it. The temperature in the furnace was measured by a system that consisted of a National Instruments data acquisition complex and fast thermocouples with a measurement error no greater than 3 K and a response time no greater than 0.1 s. The gas temperature in the heating zone (T_g) varied within the range from 673 to 783 K. The droplet heating, evaporation and fragmentation processes were recorded with a Phantom Miro M310 high-speed video camera. The framing rate was 5400 frames per second at a resolution of 768 × 768 pixels. The obtained video fragments were processed in Phantom Camera Control. The initial size of droplets (R_{d0}) and the number of secondary fragments (N_{cd}) and their dimensions (r_{cd}) were determined. The systematic errors in measurement of R_{d0} and r_{cd} was 0.0125 mm. Experiments with the same initial conditions were repeated 15−20 times in order to minimize the random error of measurement of the indicated parameters.

Distilled water, kerosene TS-1, and crude and filtered tall oil were the fluids under study. Two-fluid droplets were formed using two Finnpipette Novus electronic dispensers with a volume increment of $0.1\,\mu$l. At the first stage, a droplet of water of a given volume was formed and suspended on a holder. A droplet of a fuel component was formed next. It spread into a film over the surface of the first droplet. The concentrations of components in experiments were as follows: water — 20 vol.%, flammable

Key rheological properties of the used fluids at 298 K

Parameter	Distilled water	Kerosene TC-1	Filtered tall oil	Crude tall oil
Density ρ, kg/m^3	998.2	819	881.7	882.8
Dynamic viscosity μ, mPa $\cdot$ s	1.004	1.5	72.025	2443.963
Surface tension σ, N/m	0.072	0.024	0.035	0.041

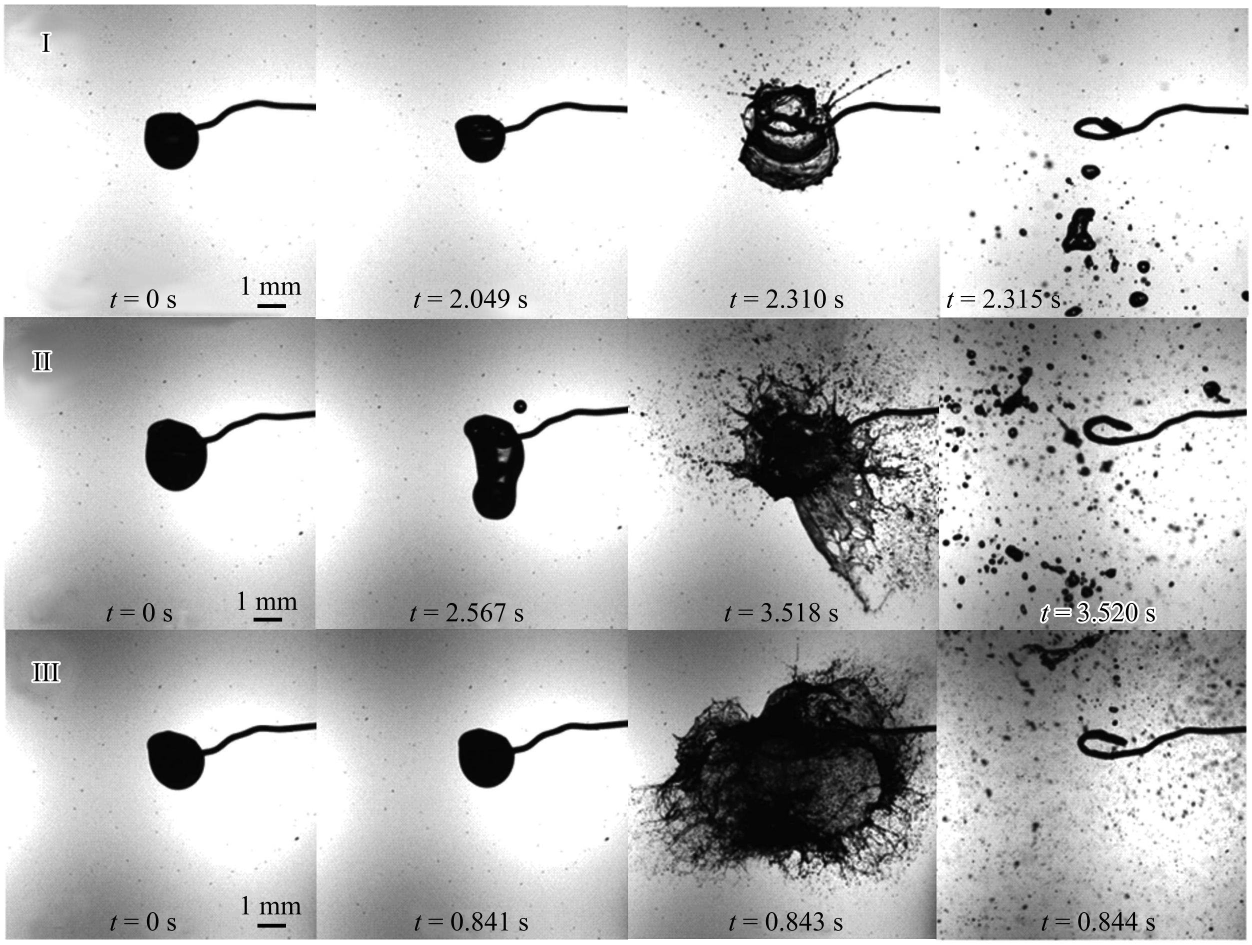

Figure 1. Video frames illustrating the process of micro-explosive fragmentation of two-fluid droplets ($T_g = 783$ K, $R_{d0} = 1.05$ mm). I — 80 vol.% kerosene, 20 vol.% water; II — 80 vol.% filtered tall oil, 20 vol.% water; III — 80 vol.% crude tall oil, 20 vol.% water.

fluid — 80 vol.%. This ratio of components provides an opportunity to achieve the maximum enhancement of the evaporation surface area [7].

The viscosity of fluids was determined using a Brookfield DV3T LV viscosity meter at room temperature of a fluid (298 K). Four spindles for measuring the viscosity of fluids within the range of $\mu = 0.001-6000$ Pa $\cdot$ s were included into the standard list of accessories of this viscosity meter [8]. Their rotation rate varied within the interval of 10–250 rpm. The error of measurement in accordance with ASTM D445 was $\pm 1\%$. Surface tension measurements were performed using a KRUSS K6 tensiometer and the du Noüy ring method at a temperature of 278 K. The instrument was calibrated by measuring the surface tension of bidistilled water (the correction coefficient was 0.995). The characteristics of components are listed in the table.

Figure 1 presents typical frames illustrating the process of fragmentation of individual two-fluid droplets heated

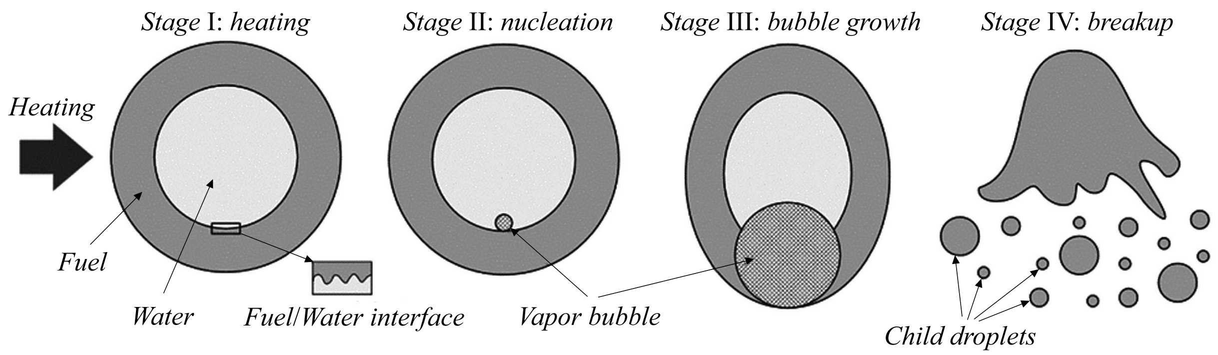

Figure 2. Physical model of the process of micro-explosive atomization of a two-fluid droplet and formation of secondary fragments.

in a high-temperature gas medium. It was found that droplets based on crude tall oil broke up consistently in the complete fragmentation (micro-explosion) regime within the entire studied temperature range, while the breakup regime of droplets based on kerosene and filtered tall oil changed from partial (puffing) to complete (micro-explosion) fragmentation in the process of heating. For example, several intense partial fragmentations of the initial droplet were followed by a certain time interval that ended with a micro-explosion, which led to complete breakup. The presented video frames demonstrate that secondary fragments of the initial droplets based on crude tall oil are much smaller in size than those corresponding to droplets based on kerosene and filtered tall oil; the largest fragments were observed in experiments with kerosene-based droplets.

In physical terms, micro-explosive fragmentation of two-fluid droplets occurs when the temperature at the water/fuel interface reaches a point corresponding to the onset of explosive water boiling [9]. The boiling point of fuel (tall oil, kerosene) is significantly higher than the one of water. This makes it possible for water near the interphase boundary to be superheated above the boiling temperature (373.15 K). Since the interphase boundary has a wavy structure, the nucleation and subsequent growth of a bubble occur in the immediate vicinity of it (heterogeneous nucleation). The results of our earlier studies [7] verify this assumption. It is local superheating of water in two-fluid droplets (resulting in chain activation of low-temperature nucleation centers [10]) that is the prime cause of their disintegration. It is fair to assume that the pressure forces of water vapor in a vapor film need to exceed the surface tension forces confining the bulk of fluid for a two-fluid droplet to be broken up. Viscosity then specifies the fraction of energy required to shift fluid layers relative to each other; i.e., the higher the fluid viscosity is, the greater the pressure of water vapor in a vapor film needs to be to form a critical bubble with subsequent disintegration of a fuel shell. This requires additional energy and time, which are spent on vaporization and buildup of the water vapor pressure. A more intense droplet fragmentation is achieved under such conditions. The corresponding estimates of the influence of rheological properties on the characteristics of micro-explosive breakup were presented in [8]. Figure 2 shows the physical model of fragmentation of a two-fluid droplet. This model features the following stages: nucleation of vapor bubbles at the water/fuel interface, movement of bubbles through a flammable fluid film, and separation of fragments of a flammable fluid and water from the parent droplet in the form of child droplets.

It was established in our earlier studies that micro-explosive atomization is the most efficient (i.e., the number of secondary fragments is maximized, while their size is minimized) when a fuel shell is formed by high-viscosity fluids, such as rapeseed oil [11]. Since the viscosity of crude tall oil is much higher than the viscosity of other studied fluids, vapor bubbles forming during heating cannot quickly reach the surface and initiate the separation of fluid fragments from a droplet (due to a strong internal friction force). More time is needed for the vapor pressure forces in a droplet to overcome its internal friction ans surface tension forces; a considerable amount of energy is accumulated within a droplet, facilitating its disintegration.

Figure 3 shows size distributions of secondary fragments $N_{cd}(r_{cd})$ and ratios of the free surface areas of a fluid after the breakup (S_1) and before it (S_0) for three types of droplets based on different flammable components and for different temperatures of the gas medium. The characteristic sizes of secondary fragments in our experiments fell within the range from 0.005 to 0.8 mm. The number of secondary fragments for droplets based on crude tall oil is several times higher than the corresponding numbers for other fuel compositions (Fig. 3, c). The distributions determined in a series of experiments reveal that crude tall oil used as a high-boiling component provides $2-3$ times more secondary fragments of a minimum size than filtered tall oil or kerosene. These results demonstrate that the higher the viscosity of a flammable component is, the greater is the number of secondary fragments of a smaller size forming as a result of micro-explosive breakup. The values of the Laplace number, which characterizes the ratio of surface tension and dissipative forces, for these fluids differ by several orders of magnitude; notably, this parameter decreases as the viscosity and surface tension of a flammable component increase. The higher the viscosity of a fluid

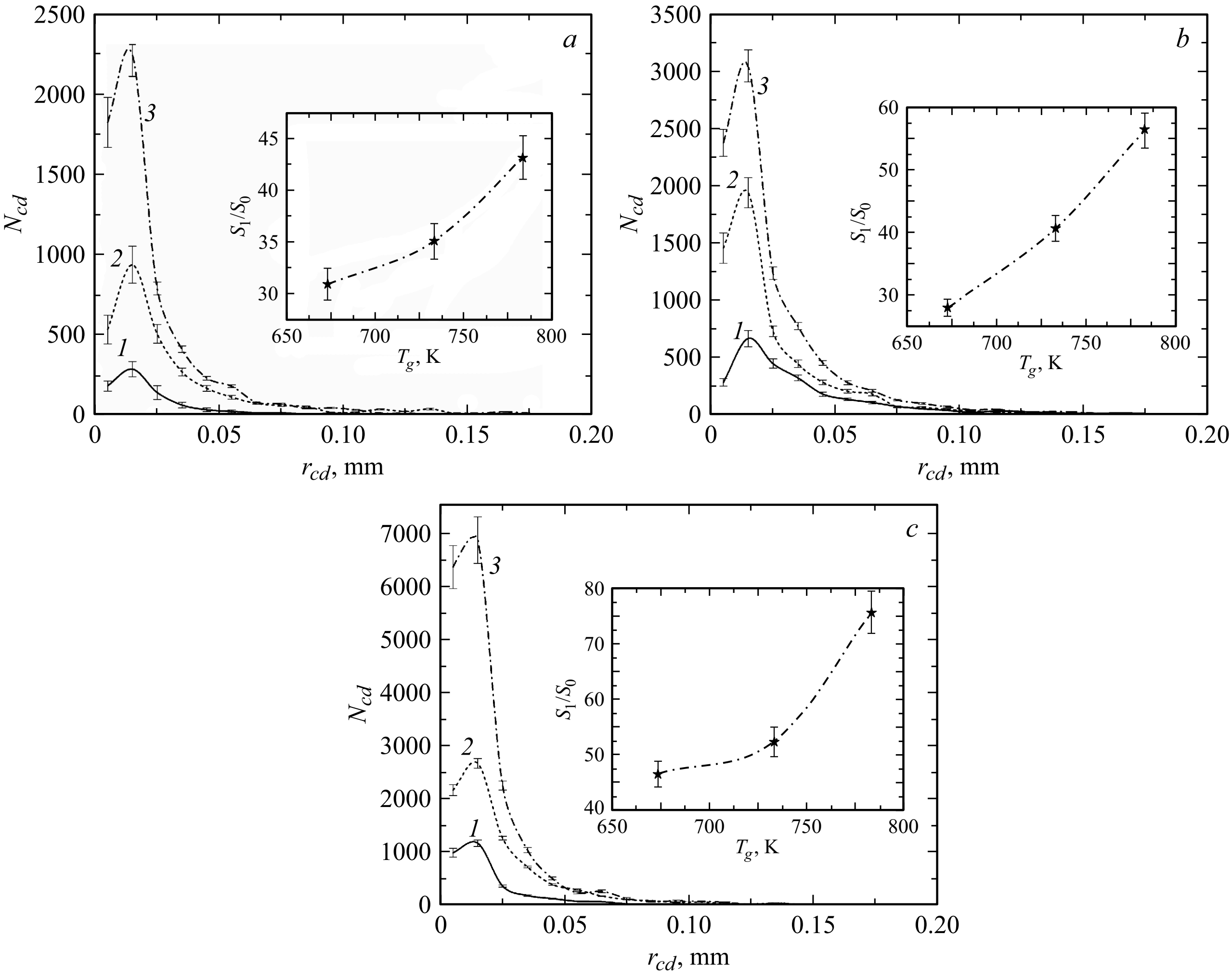

Figure 3. Size distributions of secondary fragments in the event of micro-explosive fragmentation of two-fluid droplets ($R_{d0} = 1.05$ mm) and ratios of the free surface areas of a fluid after the breakup and before it (S_1/S_0) corresponding to different temperatures of the gas medium. *a* — 80 vol.% kerosene, 20 vol.% water; *b* — 80 vol.% filtered tall oil, 20 vol.% water; *c* — 80 vol.% crude tall oil, 20 vol.% water. $T_g = 673$ (*1*), 733 (*2*), 783 K (*3*).

is, the greater is the fraction of energy, which is spent on bubble growth and initiates the disintegration of the initial droplet, turning into heat. The accumulation of this energy in a droplet is conducive to an increase in the fluid temperature and to the accumulation of additional energy that, when released, intensifies the process of fragmentation.

A comparison of the ratio of areas after the breakup and before it also demonstrates that crude tall oil provides the greatest possible enhancement of the fluid surface area. At a temperature of 783 K of the gas medium, the free surface area of a fluid increased by a factor of more than 70. The corresponding enhancement factor for kerosene and filtered tall oil did not exceed 45 and 60, respectively. These results suggest that the use of micro-explosive atomization of droplets based on crude tall oil is a viable way to produce synthesis gas in reactors.

Thus, the obtained experimental data provided an opportunity to identify the differences in parameters of secondary fragments forming in micro-explosive fragmentation of droplets of multicomponent fuel based on tall oil. The use of crude tall oil allows one to increase the number of secondary fragments by a factor of more than 3 (compared to kerosene and filtered tall oil).

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Conflict of interest

The authors declare that they have no conflict of interest.

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