EXPLOSIVE DISINTEGRATION OF TWO-COMPONENT DROPLETS IN A GAS FLOW AT ITS TURBULIZATION

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The experimental results shown that the mode of droplet disintegration dominates in the laminar flow, and the intensive fragmentation is prevalent in the turbulent flow during almost the entire time of heating. Typical dependences of the time of drop heatup before disintegration or fragmentation on the temperature, flow rate, structure and regime (laminar and turbulent) are established. The studies are conducted with heated air and flue gases to ensure the application of the research results in the technology of thermal and flame cleaning of liquids from irregular impurities. It is shown that in the flow of combustion products the droplet disintegration occurs 15–20% faster than in the air flow. In this case, the explosive puffing is more often realized. At high temperatures (more than 400 °C) the characteristics of the explosive droplet disintegration in the studied flows are almost identical (differences in disintegration times do not exceed 5% at different flow turbulization). At lower temperatures, the disintegration times differ 3–4 times for the range Re=2200–3400. In this case, the more Re is, the more intense is the fragmentation of two-fluid droplets throughout the heating time. Due to explosive disintegration of intensely evaporating two-fluid droplets the growth of the relative area of evaporation was 10–25 times.

Keywords: *two-component drops; intense heating; explosive disintegration; gas flow; flow turbulization; air and flue gases.*

1. Introduction

Modern systems of flame and thermal water purification from irregular impurities, unfortunately, have a rather low efficiency [1–3]. This is due to the necessity to re-feed the purified liquid into the heating chamber. The number of such cycles can be quite large. Impurities cannot evaporate or burn out fast enough while the liquid flow passes through the chamber space. This increases the energy consumed to operate these systems and the duration of the relevant processes [1–3]. A rational way to solve this problem may be the disintegration of liquid drops to the level of hundreds or even tens of micrometers. However, as it may be inferred from experiments of [4], such small drops may be entrained from the heating chamber or stick to its walls due to high gas velocities. Therefore, puffing droplets in advance (i.e. before feeding to the heating chambers) can lead to additional difficulties and limitations. In this case, it is advisable to puff the drops in the chamber during the heating process. The most attractive from the point of view of realization, the required energy and time is reaching the conditions of explosive disintegration (intense puffing) of droplets with the formation of aerosol (most often a mixture of aerosol, vapor and air is formed).

Basically, today there are only the results of experimental studies (for example, [5–10]) of the conditions and characteristics of the explosive disintegration of intensively evaporating drops of liquids, emulsions, solutions and suspensions with the formation of aerosol. The modes of disintegration (namely, breakdown, dispersion or partial fragmentation, and complete disintegration) of two-liquid water droplets were investigated in [5–10]. The limit conditions for the complete explosive disintegration of two-liquid mixed and non-mixed drops were established. It was found that the greatest impact on the droplets disintegration is exerted by the temperature of the gas medium and the concentration of components. In addition, authors of [5–10] investigated the influence of the temperature of gaseous medium and the material of the holder on the time of disintegration of two-fluid drops, as well as on the consequences of such disintegration. The main mechanism of droplet disintegration was associated with overheating of the inter-component boundary above the water boiling point (100–120 °C) [5, 6]. At that, the determining influence was exerted by the surface tension of the droplet, which restrained the free exit of the vapor bubbles formed at the inter-component boundary. When the steam pressure in the drop exceeded the limit value, the explosive disintegration of the latter occurred with the formation of a droplet aerosol, fog and smog. However, in [5–10] the influence of the structure of the heated incident gas flow (laminar or turbulent) on the evaporation and disintegration characteristics of two-liquid droplets was not studied. A comparative analysis of characteristics of the explosive disintegration of liquid droplets during heating in the air flow and flue gases (they act on potential effects of droplets turbidity during heating [10–13]) has not been carried out yet.

The objective of this work is the experimental study of the regularities of heating, evaporation and explosive disintegration of two-component drops in the gas flow at the turbulization. It is important to vary the main characteristics of the processes within the ranges corresponding to the group of promising gas-vapor technologies, in particular, considered in [5–10].

2. Experimental setup and procedures

Two components were used in experimental studies: water and transformer oil. With the use of the latter, all the main regularities of the explosive disintegration of two-liquid droplets in the experiments [13] were analyzed. The average disintegration times were established with respect to similar characteristics for two-component droplets with the use of oil, fuel oil, kerosene and ethyl alcohol as a liquid fuel. As a result of the merger of initial drops of water and oil, a two-component drop was obtained. The main properties of the components are presented in Table 1. *Rhodamine b* fluorophore was added to water to control the temperature in the two-fluid droplet by *Planar Laser Induced Fluorescence (PLIF)* method similar to the experiments of [10].

Table 1. The main properties of the investigated components of a two-liquid drop

Component	Density, thermal conductivity, heat capacity, temperature diffusivity	Kinematic viscosity	Surface tension	Boiling temperature	Vaporization heat
Transformer oil	ρ=877 kg/m^3, λ=0.12 W/(m·°C), C=1670 J/(kg·°C), $a=\lambda/(C\cdot\rho)=8\cdot10^{-8}$ m^2/s	$22\cdot10^{-6}$ m^2/s at 20 °C, $0.295\cdot10^{-6}$ m^2/s at 100 °C	$26.15\cdot10^{-3}$ N/m	320 °C	0.209 MJ/kg
Water	ρ=1000 kg/m^3, λ=0.6 W/(м·°C), C=4200 J/(kg·°C), $a=\lambda/(C\cdot\rho)=14\cdot10^{-8}$ m^2/s	$1.006\cdot10^{-6}$ m^2/s at 20 °C, $2.56\cdot10^{-6}$ m^2/s at 100 °C	$72.86\cdot10^{-3}$ N/m	100 °C	2.258 MJ/kg

To generate the initial droplets of the desired size two *Finnpipette Novus* pipettes were applied (with volume variation step of 0.1 μl). The initial volume of the two-component drop in the experiments varied in the range V_d=10–25 mcl. This corresponded to the radius range R_d=1.3–1.8 mm. A drop of liquid fuel component was suspended on the holder. Further the drop of water was placed on this drop using the second pipette. The work [10] provided the results of studying the effect of the scheme of droplets placement on the holder on the conditions of their heating and disintegration, as well as the differences in times and modes of explosive disintegration of two-liquid droplets when changing their shell and core from combustible to non-combustible components.

In the course of the experiments the mode of gas flow was changed. *Leister CH 6060* hot–air blower (air velocity of 0.5–5 m/s) and *Leister LE 5000 HT* air heater (temperature range of 20–1000 °C) changed the gas flow velocity U_a and temperature T_a. The flow was formed in a transparent hollow cylinder (silica-glass, inner diameter of 0.1 m and wall thickness of 2 mm). In this cylinder, three holes with a diameter of 10 mm were made for laser illumination of the droplet, its introduction into the flow of high-temperature gases and registration of the studied fragmentation processes. The temperature of the gases in the cylinder was measured using a complex consisting of a high-speed data acquisition system *National Instruments 9213* and two low-inertia chromel-aluminum thermocouples (temperature range of 0–1200 °C, accuracy of ± 1 °C, and inertia of 0.1 s). The velocities of the high-temperature gas flow (U_a) were measured using the optical method of *Particle Image Velocimetry (PIV)* similar to experiments in [10]. The U_a values were recorded just before the main experiment, i.e. before the drop was placed in a cylindrical channel. The registration error of velocity U_a did not exceed 2%. Since the air flow in the scheme with convective heating had sufficiently high T_a temperatures, it was possible to register the U_a values only with the use of non-contact optical method.

The investigated two-component drop was placed on a miniature steel holder (diameter of 0.6 mm), which was introduced into the flow of high-temperature gases by means of a mechanized coordinate device. High-speed camera recorded high-speed processes of disintegration of two-component droplets. Video frames were processed using *Phantom Camera Control software*. The frequency of shooting during the experiments was 1000–3000 frames per second.

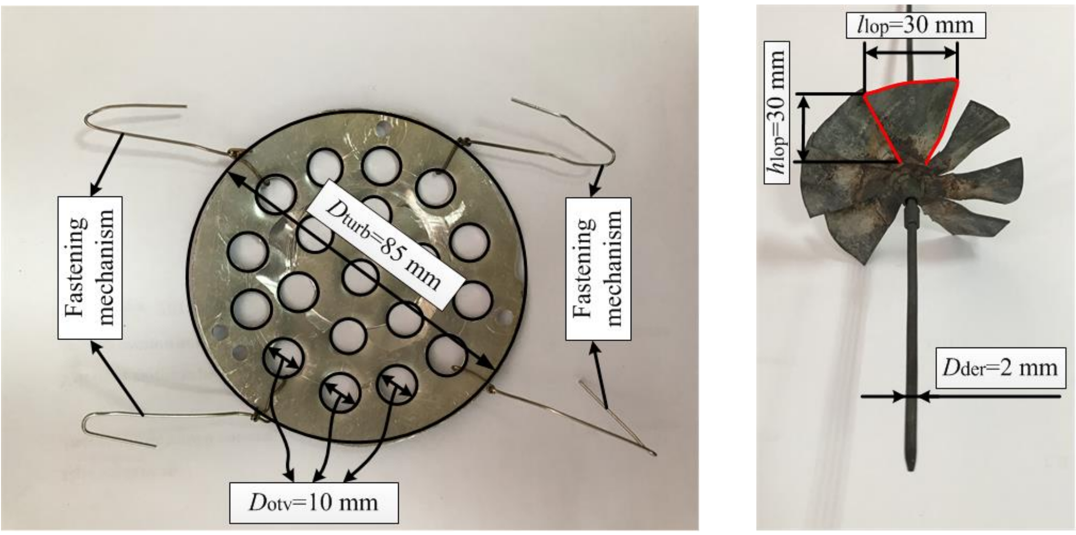
In [10] the expediency of application of the steel holder used in the present work in comparison with wires and rods is justified (the latter essentially influenced the rates of heatup and evaporation of drops of homogeneous and multicomponent liquids). In the use of other typical holders (phosphorous, aluminum, copper, nichrome, brass, etc.), it is advisable to take into account the relevant results of comparison of droplet disintegration times obtained in the experiments [10].

The change of gas flow parameters was realized using two types of turbulators: stationary and rotating. The main dimensions, configuration and appearance of the latter are presented in Fig. 1.

The degree of the air flow turbulence was determined by calculating the Reynolds numbers. In particular, the estimates have shown that without turbulators, the characteristic Reynolds numbers did not exceed 2300 in the entire range of flow velocity variation. While applying turbulators (Fig. 1) the Reynolds numbers reached up to 3200–3500. In the case of a rotating (dynamic) turbulator, the Re values were 1.2–1.5 times higher than in the case of a stationary turbulator.

A high-speed video camera served to register the processes of heating, evaporation and disintegration of two-component drops. The obtained videograms were processed using software systems for continuous tracking of dynamic objects, namely, *Tema Automotive and Actual Flow software*. The initial size of the R_d droplets and the total surface area of the liquid evaporation S before and after disintegration were determined.

The stages of video processing are described in detail in [10]. It was assumed that the drop has the shape of a sphere, and its mid-section represents a circumference. The formula $R_d=(S_m/\pi)^{0.5}$ was used to calculate the average radius of the initial drop R_d before disintegration and the radii of the drops R_{dn} after disintegration. Determination errors for R_d did not exceed 2.5 %. Then, using the formula $S=4\pi R_d^2$, the total surface area of the droplet evaporation before and after the disintegration was determined (Fig. 2).



a *b*

Figure 1. Turbulators: *a* – stationary; *b* – rotating

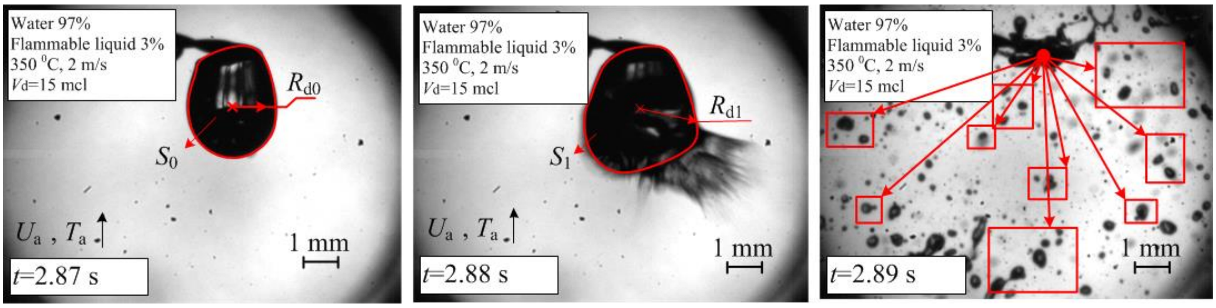


Figure 2. Scheme of registering the heated droplet disintegration and the aerosol forming

It should be noted that random errors in determining the radii of R_d drops are due to the continuous change in the configuration of the surface of the heated and intensely evaporating two-liquid drop. Averaging of experimental results (from 5 to 10) within the series allowed minimizing errors and registering a fair reproducibility of the main recorded parameters.

Table 2 lists the recorded characteristics of the process in the experiments and shows the systematic errors of measuring instruments. Random errors calculated in the analysis of the results correlation in a series of experiments are reflected in the next section of the work in the form of confidence intervals.

Table 2. The main registered characteristics and errors of their determination

Physical value	Device / measuring method	Systematic errors
Air temperature (T_a)	Thermal transformer (IT-8)	± (0.2+0.001T)
Air flow velocity (U_a)	Particle Image Velocimetry (PIV)	± 2%
Drop volume (V_d)	Finnpipette Novus dosers	±0.05 mcl
Drop radius (R_d)	High-speed cameras: Phantom Miro M310 and Phantom Fastcam SA1; Tema Automotive software	≤ 4%

Water temperature in a drop (T_d)	Planar Laser Induced Fluorescence (PLIF)	±1.5–2 °C
Time of drop heatup and evaporation with remaining wholeness (τ_h); Drop disintegration time (τ)	High-speed cameras: Phantom Miro M310, Phantom Fastcam SA1, and Phantom V 411; Tema Automotive software	≤ 4%

3. Results and Discussion

Similar to the experiments of [10, 13] using the *PLIF* method, this work establishes temperature fields of a two-component liquid drop during its heatup up to explosive disintegration (Fig. 3). The temperature at the inter-component boundary before disintegration exceeds 100 °C, i.e. the droplet disintegration is accompanied not only by intense vaporization of the combustible liquid, but also by boiling of water at the inter-component boundary. The temperature range of 100–120 °C of the inter-component boundary is typical for all the experiments ended with the two-component drop disintegration. Such temperatures were achieved for different component compositions of droplets and under different heating conditions (in the studied laminar and turbulent gas flows). Therefore, it can be concluded that the mechanism of explosive disintegration of the droplet is similar to that described in [10]. In particular, the disintegration of the two-component drop cannot be caused by a significant overheating and boiling of the liquid combustible component. It is quite difficult to heat up the entire volume of water to the boiling point due to its high heat capacity [10]. The mechanism of droplet puffing is based on nucleation of small bubbles filled with vapors of a more heated liquid (in our case, it is a liquid combustible component) at the inter-component boundary. Due to the growing size of such small bubbles, their merger and shift in the two-fluid drop, bubbles with higher pressure appear. As soon as their pressure exceeds the one caused by the surface tension forces acting on the drop, the latter disintegrates. If the increase in the bubble pressure in the drop was significant, then the disintegration of the initial drop was recorded. When the pressure increased slowly, then there were processes of multi-scale fragmentation of the droplet or its complete disintegration.

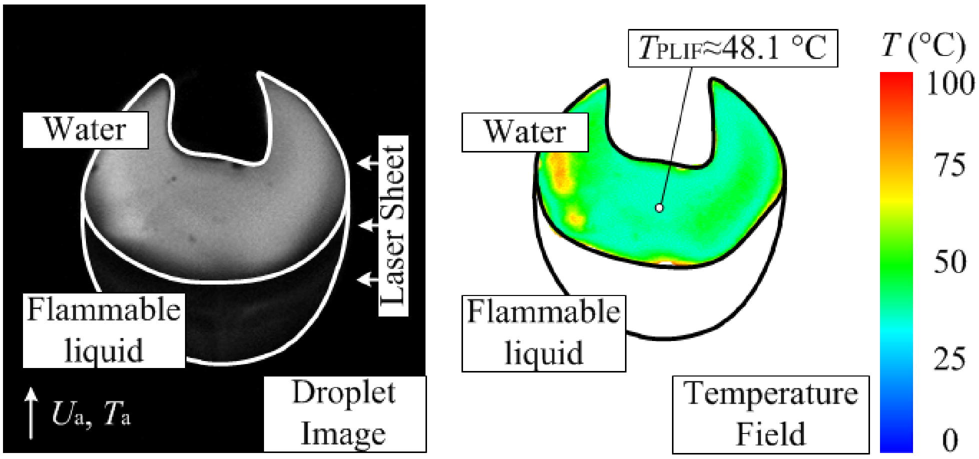
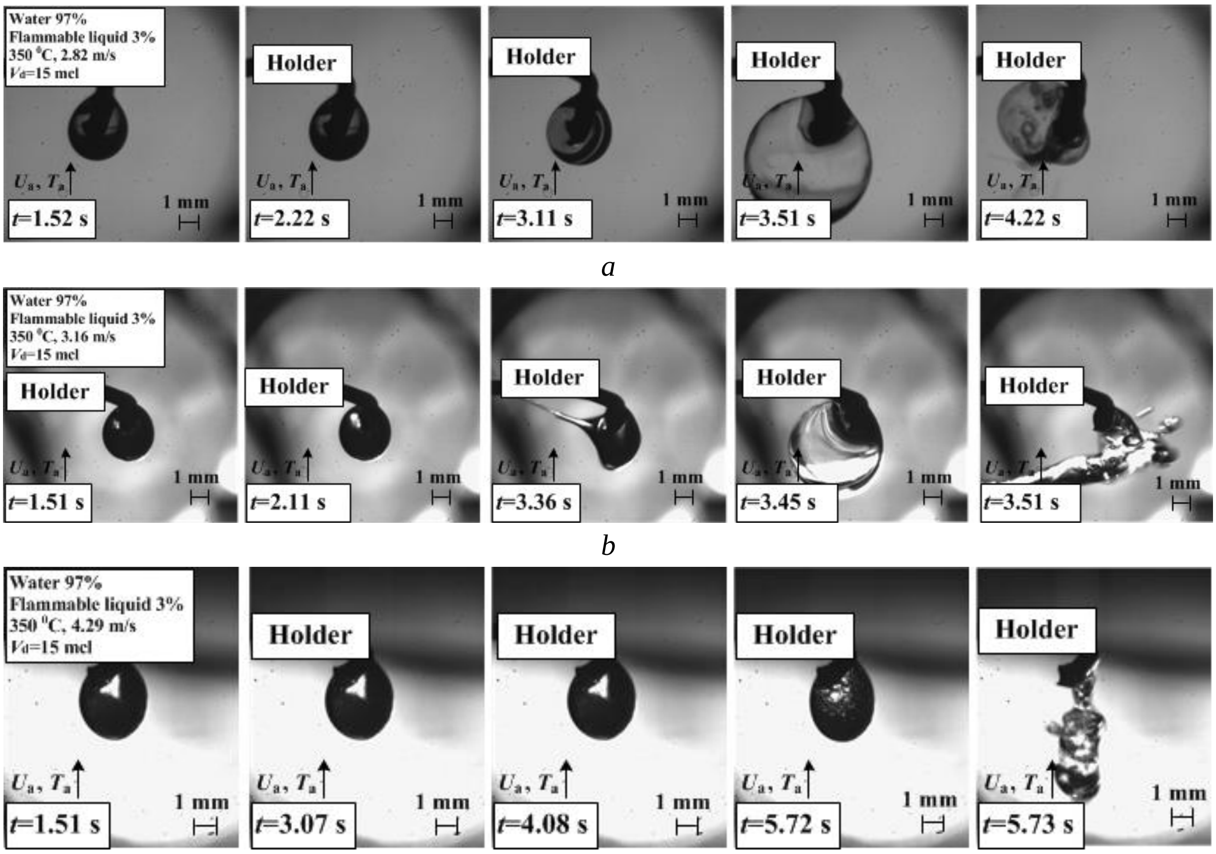


Figure 3. Typical frame and temperature field of two-component droplet (R_d =1.53 mm, water 50 wt%, flammable liquid 50 wt%) at the T_a = 200 °C, τ_h = 7 s

Fig. 4 presents typical video frames illustrating the processes of heatup, evaporation and disintegration of two-liquid drops in gas flows. The effect of flow turbulization was as follows. When using a laminar flow, the two-fluid drop was almost motionless (no significant surface vibrations were registered), and in the case of a turbulent flow, the two-fluid drop was significantly deformed: the surface was transformed and the drop took the form of a sphere, an ellipsoid, a pancake, etc. The higher was the turbulence of the flow, the more significant was the surface transformation. Turbulent flows, unlike laminar, reduced the probability of complete destruction (explosive disintegration) of two-liquid droplets. The reason was that due to the successive oscillations of the droplet there was not enough time for the formation of a steam bubble or several fairly large bubbles, characteristic of the droplet disintegration regime with gas-vapor cloud generation. Instead, the experiments with turbulent gas flow registered successive nucleation, motion to the free surface of the droplet and release of small bubbles, as well as separation of small fragments of liquids from the initial (parent one).



a

b

c

Figure 4. Frames with disintegration or fragmentation of droplets (R_d =1.53 mm) at different gas flow modes: *a* – laminar; *b* – turbulent (stationary turbulator); *c* – turbulent (rotating turbulator)

Intensification of droplet heating due to the gas flow turbulization changed the dispersion mode from explosive disintegration to partial fragmentation. As a result, despite the intensification of heating, the existence times (full evaporation or disintegration) of two-liquid droplets in turbulent gas flows were higher than in laminar ones at identical temperatures. It should also be noted that in turbulent flows the appearance of heated two-component drops differed from those recorded in experiments with laminar flows. In particular, Fig. 4 clearly shows that in the case of flow turbulization, the drop became opaque from the first seconds in contrast to the experiments in laminar flow. This is due to intense displacement of the inter-component boundaries, their rupture and disintegration (fragmentation) during the droplet transformation due to flow turbulization by turbulators. A drop became more transparent or, contrary, darker. It was possible to record steadily an important factor – a turbidity of the water component of the two-fluid drop during heating. The reasons for this effect are explained in detail in [11, 12] and they are due to changes of the molecular level of the water composition due to the reaction of water with impurities.

Turbulators significantly influenced the gas flow velocity in the vicinity of the two-liquid droplet. The main regularity in the study of disintegration conditions in a laminar flow was that with an increase in the gas flow temperature, the disintegration times decreased nonlinearly (almost exponentially) (Fig. 5). And in the case of using turbulent flows such patterns were not always recorded. This is most likely conditioned by the fact that in turbulent flows with varying temperature, transitions from one mode of droplet disintegration to another (from the disintegration of the parent droplet to its stage fragmentation) are the most probable. In Fig. 4, the temperature range extremes are different for all curves. This is due to the fact that for different gas flow regimes there were different conditions of drop separation (breakdown) from the holder or their intense boiling up before entering the central part of the model chamber.

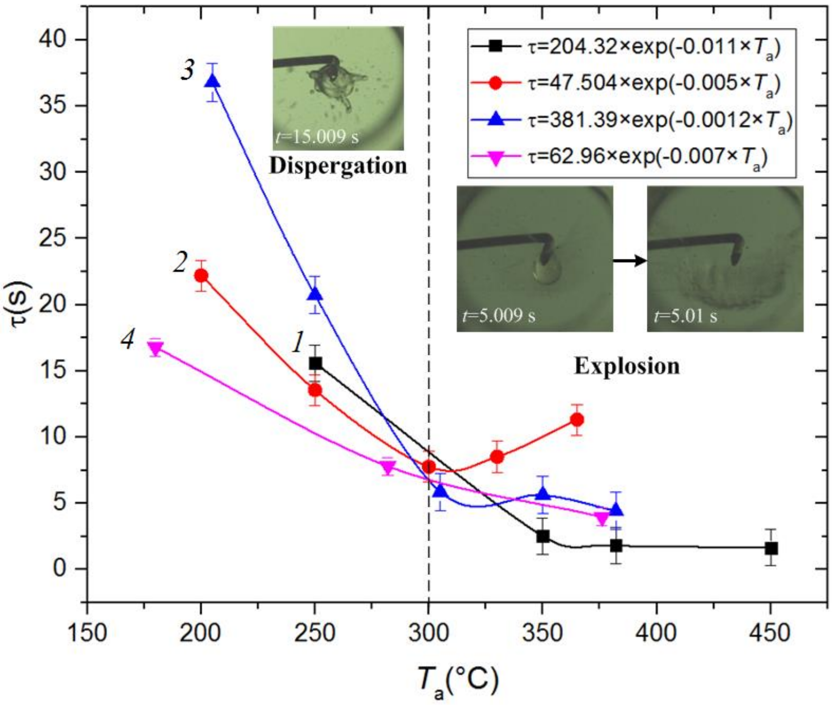


Figure 5. Dependences of heating times of two-component drops up to the conditions of explosive disintegration on temperature (composition: 3% of oil and 97% of water, η_{oil} =3%, U_a =2 m/s, V_d = 15 mcl) air flow: *1* – laminar; *2* – turbulent (stationary turbulator); *3* – turbulent (rotating turbulator); 4 – flue gases (combustion products of kerosene)

In addition to experiments with air flow, experiments were conducted with flue gases, products of kerosene combustion (curve *4* on Fig. 5), since in typical units of thermal purification of water from impurities, as well as in waste boilers, aerosols are often mixed with flows of combustion products. It was found that when a two-fluid drop was placed in the combustion product flow, the disintegration times were less (by 15–20% compared to air under identical conditions), and the disintegration temperatures were also lower (in particular, Fig. 5 shows that the minimum temperature at which the disintegration conditions were realized in all the studied gas flows was equal to 300 °C). At temperatures of 200–300 °C in a laminar flow, the conditions of explosive disintegration were recorded, but the recording was unstable, i.e. in each third or fourth experiment at identical temperatures. Only fragmentation was recorded in turbulent flows. At temperatures above 300 °C, the explosive disintegration was the main mode. It is clearly seen that when the temperature increases, the differences in the times τ for the studied flows significantly decrease. It can be concluded that the disintegration times of two-liquid droplets in laminar and turbulent gas flows are almost identical in such conditions. However, in experiments with a stationary turbulator (curve 2 in Fig. 5) there was a slight increase in the time of explosive disintegration of a two-fluid drop with an increase in the temperature of the gas flow from 300 to 370 °C. This is because the air flow at the stationary turbulator output had a non-uniform velocity profile. As a result, the speed of droplet transformation increased. The higher is the temperature of the air flow, the more significant are these transformations. As a result, the rate of heatup and evaporation of the droplet increased, but the times of its heatup to the disintegration conditions began to increase as well. In experiments with a rotating turbulator such patterns were not recorded, since the latter swirled the flow and the drop, respectively. It was stretched sequentially in the flow direction and then in the transverse direction, and its fragmentation was not that pronounced as in experiments with a stationary turbulator. The heatup time up to disintegration non-linearly decreased in the entire temperature range (Fig. 5).

In the conducted experiments, a certain pattern is observed. The disintegration of a two-liquid droplet in a turbulent flow (especially in experiments with a rotating turbulator) of flue gases was accompanied by a loud slap (characterizing the provision of conditions for the formation of a shock wave), significantly exceeding the slap in a laminar flow of heated air. This is most likely conditioned by the fact that in the flow of combustion products, the droplet surface is supplied with additional heat due to the emission of flue gases and vapors. Their turbulization only amplified this effect.

In the conducted experiments one of the key was the dependence of the times of complete disintegration of two-fluid droplets on the initial size of the initial drop. The type of the obtained dependences is essentially nonlinear (with a change in the sign of the derivative in the central part of the range of R_d radius variation), which indicates a significant influence of the size of the two-fluid drop on a group of interrelated and differently directed processes that lead to the disintegration of initially two-component drops. However, in a comprehensive analysis of Fig. 6 it can be concluded that in general, the disintegration times of two-liquid droplets with a 2 times increase in their size change by no more than 15–20%. In this case, the confidence intervals for each of the presented curves intersect, which indicates a rather moderate effect of R_d on the times τ. It should also be noted that the volume of the two-component drop significantly affects its shape and contact area with the holder. The larger is the droplet size, the higher is the probability of its falling from the holder or intensive heatup from the side of the latter.

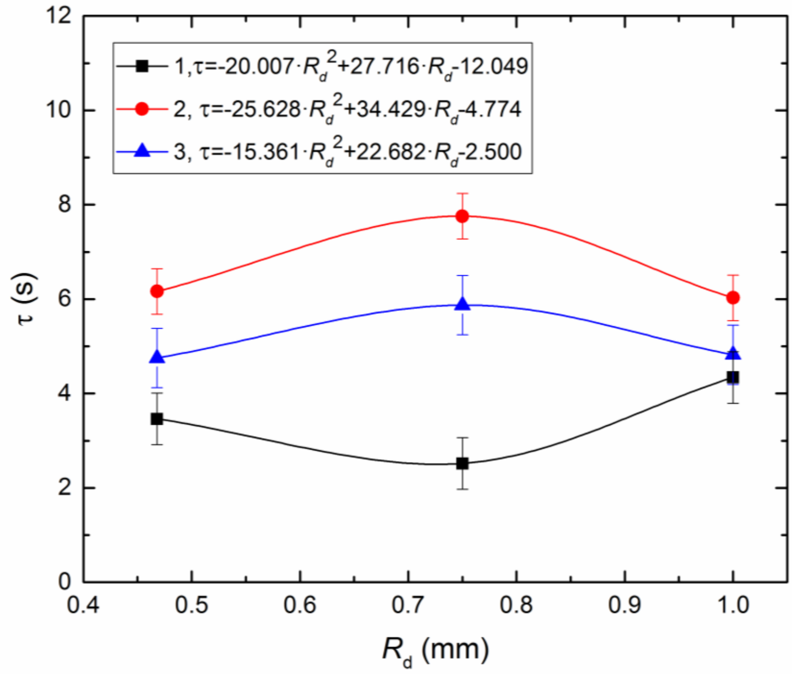


Figure 6. Dependence of the droplet disintegration time on the size of two-component droplets (T_g=350 °C, U_a =2 m/s, composition: 3% of oil and 97% of water): *1* – laminar flow; *2* – turbulent flow (stationary turbulator); *3* – turbulent flow (rotating turbulator)

Complicated dependences of disintegration time on the size of two-liquid droplets are largely conditioned not only by the influence of the type of gas flow, but also by the possibility of fixing a drop of one or another size on the holder. The minimum disintegration times for varying sizes of two-liquid droplets correspond to the laminar flow. This is due to the fact that no significant fluctuations (deformations) of the droplet were recorded in the laminar flow, and less time was required for the formation and disintegration of vapor bubbles in the droplet for the subsequent disintegration of the droplets (Fig. 7).

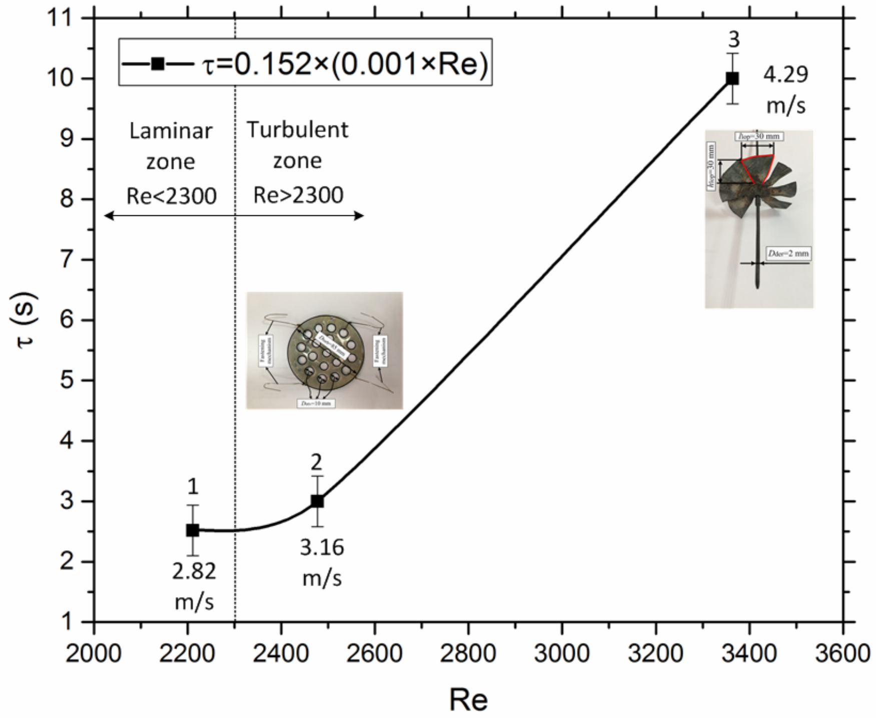


Figure 7. The results of generalization and criteria treatment of experimental data (T_g=350 °C, composition: 3% of oil and 97% of water, V_d=15 mcl); the relative times of droplet disintegration with the time scale τ_m=1s are given (since in the region of high flow temperatures, over 500 °C, this value characterizes the maximum heatup time to disintegration)

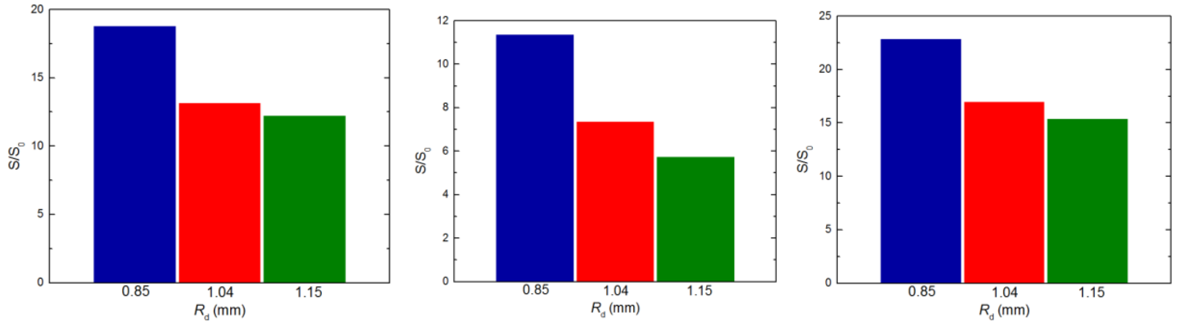
Fig. 7 presents the criterial treatment in the form of the dependence of the disintegration times of the two-fluid drops on the Reynolds numbers. Values 1–3 indicate the heating modes and the corresponding values of Re. The obtained experimental dependence (Fig. 7) shows that as Reynolds numbers increase, the droplet heating times before disintegration increase. This is due to the fact that in a more turbulent flow, the droplet deformation in the heated air flow is intensified, small bubbles are formed, mixed, and quickly leave the free surface of the droplet without merging into a large bubble and without appropriate disintegration.

Reynolds numbers are determined as follows:

$$\mathrm{Re} = \frac{U_\mathrm{a} \cdot 2R_\mathrm{c}}{\nu_\mathrm{a}},\ R_\mathrm{c} = 0.05\ \mathrm{m},\ \nu_\mathrm{a} = 63.77 \cdot 10^{-6}\ \mathrm{m}^2/\mathrm{s}\ \text{at}\ T_\mathrm{a} = 350\ ^\circ\mathrm{C}. \tag{1}$$

In the analysis of consequences of explosive disintegration (Fig. 8) of two-liquid droplets it was found that in a gas flow with a rotating turbulator, a drop aerosol with a maximum number of small fragments (droplets) was obtained. As a result, the surface area of evaporation of liquids in such conditions increased more than 20 times.

Despite the fact that in the three studied gas flows, different regimes of heating, fragmentation and disintegration of two-liquid droplets were implemented, a significant increase in the area of two-component droplets evaporation was provided in each of them. This integral result allows us to conclude that the explosive disintegration of multicomponent droplets can be a tool for evaporation enhancement in any gas medium at an adequate choice of temperature and taking into account the proportion (concentration) of the components. The present work and [10, 13] give the corresponding approximations for predicting effective conditions of explosive disintegration of intensely heated multicomponent drops.



a *b* *c*

Figure 8. The ratio of the area of evaporation of two-component drops to the concentration of the flammable liquid (oil): *a* – laminar flow; *b* – turbulent flow (stationary turbulator); *c* – turbulent flow (rotating turbulator)

The obtained experimental results are important for fundamental research in the field of non-contact temperature measurements of droplets of solutions, emulsions and suspensions under radiation, and convective and conductive heating. In particular, it is emphasized in [14–23] that reliable experimental information on essentially non-stationary and non-uniform temperature fields of evaporating droplets is not sufficient. The lack of a reliable experimental database on such temperature fields still hinders the development of models of heating and evaporation of fuel droplets. The development of these models is extremely important for predicting the conditions for the effective preparation of fuels for combustion and the implementation of this process with high technical and economic indicators and minimal negative environmental consequences.

4. Conclusion

(i) The analysis of the modes of two-liquid drop disintegration in turbulent and laminar flows allowed concluding that the most probable is the disintegration of the drop with the formation of an aerosol at relatively low flow rates.

(ii) The temperature of the gas flow is the main factor that has a significant impact both on the disintegration times and on the flow rates. The temperature variation allows obtaining different modes of drops puffing: fragmentation, disintegration, and breakdown.

(iii) The consequences of the two-liquid droplet disintegration are significantly influenced not only by the gas flow regime (laminar or turbulent), but also by the size of the initial two-liquid droplets. Under conditions of intense turbulent flow, the relative evaporation area increased more than 20 times.

Acknowledgments

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Nomenclature

a – thermal conductivity, m^2/s;

C – specific heat, J/(kg·°C);

D_{der} – holder diameter, mm;
D_{otv} – diameter of openings of the stationary turbulator, mm;
D_{turb} – diameter of the stationary turbulator, mm;
h_{lop} – blade width of rotating turbulator, mm;
l_{lop} – blade length of rotating turbulator, mm;
R_d – drop radius, mm;
R_{d0} – initial radius of two-component drop, mm;
R_{d1} – drop diameter before disintegration, mm;
R_c – radius of cylindrical channel, mm;
R_{dn} – average radius of drops in a group, mm;
Re – Reynolds number;
S – total area of evaporation surface of droplets after Cdisintegration, mm^2;
S_0 – initial area of drop surface, mm^2;
S_1 – drop surface area before disintegration, mm^2;
S_m – mid-section area, mm^2;
T_a – gas flow temperature, °C;
T_d – temperature in a drop, °C;
t – time, s;
U_a – high-temperature gas flow velocity, m/s;
V_d – drop volume, μl.

Greek

η_{oil} – concentration of flammable liquid, %;
λ – thermal conductivity, W/(m·°C);
ν_a – kinematic viscosity of air, m^2/s;
ρ – density, kg/m^3;
τ – drop disintegration times, s;
τ_h – times of drop existence, s;
τ_m – scale of drop disintegration time, s.

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