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Evaporation of oil-water emulsion drops when heated at high temperature

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Abstract. An experimental study on conditions and main characteristics for high-temperature (more than 700 K) evaporation of oil-water drops is presented. The high-temperature water purification from impurities can be the main practical application of research results. Thus, the heating of drops is implemented by the two typical schemes: on a massive substrate (the heating conditions are similar to those achieved in a heating chamber) and in a flow of the heated air. In the latter case, the heating conditions correspond to those attained while moving water drops with impurities in a counter high-temperature gaseous flow in the process of water purification. Evaporation time as function of heating temperature is presented. The influence of oil product concentration in an emulsion drop on evaporation characteristics is discussed. The conditions for intensive flash boiling of an emulsion drop and its explosive breakup with formation of the fine droplets cloud are pointed out. Heat fluxes required for intensive flash boiling and explosive breakup of a drop with further formation of the fine aerosol are determined in the boundary layer of a drop. The fundamental differences between flash boiling and explosive breakup of an emulsion drop when heated on a substrate and in a flow of the heated air are described. The main prospects for the development of the high-temperature water purification technology are detailed taking into account the fast emulsion drop breakup investigated in the paper.

1. Introduction
The classification of emulsions involves three types, such as water-in-oil (W/O) emulsion, oil-in-water (O/W) emulsion and multiple emulsion [1]. When water globules are dispersed in the oil product volume, such system is usual to name the W/O emulsion. In the opposite case the emulsion is named as the O/W one. Multiple emulsion is a complex system such as water-in-oil-in-water (W/O/W) emulsion and oil-in-water-in-oil (O/W/O) emulsion. Note that each emulsion has advantages and disadvantages. This is related to their application in industry. Consequently, in some fields of industry any emulsion is a desired result of the working process. However, for example, for the oil and gas industries the formation of the W/O emulsions is a serious problem, e.g. oil spills at sea.

Another interesting line of research in the emulsification field is a water-in-diesel emulsion (WiDE) as an alternative fuel for compression ignition engines [2]. The main result of such investigations is a reduction of NO\textsubscript{x} emissions and particulate matters (soot particles) due to decrease in temperature of the combustion products. The latter is a result of the water vaporization and the consequent dilution of the gas phase species. Moreover, the presence of water decelerates the formation of soot particles and their burnout. As mentioned in [2],
such the attention to the WiDE study is conditioned by the lack of understanding processes of combustion and formation of particulate matters, evaporation and mixing of emulsions, as well as the nature of microexplosion phenomena when heated. There are some findings on the incorporation of nano-particles in the WiDE fuel for the enhancement of the combustion and emission characteristics [3]. Study [3] also reports the complexity of the microexplosion phenomenon investigations.

The phenomenon of the microexplosion includes that the water in the W/O emulsion reaches the superheated stage faster than the oil product, and as a result vapor expansion breakup occurs. The implementation of this phenomenon aids to atomize the oil product and, consequently, to improve in the air and fuel mixing, as well as to increase the combustion efficiency [3]. However, the mechanism of the microexplosion phenomenon is poorly understood [2, 3]. In particular, there is the lack of the experimental data on the influence of different parameters on the nature of the phenomenon.

Oil-in-water emulsions is also important in the oil and gas industry as a displacing fluid for enhanced oil recovery [4].

In this research we show how the explosion phenomenon of the O/W and W/O emulsion droplets can be applied in thermal cleaning of water polluted by oil products. To date, there exist the large group of methods for water purification from different impurities and anthropogenic emissions. Particularly, among these are thermal, chemical, biological, stratifying and membrane technologies [5-7]. We report in detail about the thermal purification of the contaminated water, because this way allows the removal of the wide group of impurities. This type of the purification of the contaminated water has a group of disadvantages involving the cyclic supply of the polluted water into heaters and high costs due to the significant fuel consumption and the long-continued process of cleaning.

Importantly, the rapid development of the experimental techniques of optical diagnostics and high-speed video recording contributes to the experimental research on the evaporation of two-phase liquids even under high temperatures of heating. The analysis mentioned above shows that due to the lack of experimental data and numerical results on the evaporation mechanism of the O/W and W/O emulsion droplets it is suitable to determine their evaporation characteristics. Since liquid pollutants are the main components of the typical emulsified and slurry fuels, then the study of vaporization of the W/O and O/W emulsion droplets under high temperatures of heating is critically important in oil and gas industries, and thermal purification technologies.

The purpose of this research is to establish characteristics for vaporization of water droplets containing the oil product at different volume concentrations during the high-temperature heating.

2. Experimental Setup and Methods

2.1. Materials

We use the distilled water meeting the Russian standard GOST 6709-72. Since the volume concentration of oil product varies from 15 % to 70 %, then, roughly speaking, we consider both the W/O and O/W emulsion droplets. The research involves the utilization of several oil products such as kerosene TS-1, 92 RON petrol, fuel oil M-100, turbine oil TP-30, transformer oil. However, the main experimental results (i.e. curves) report the vaporization characteristics of the water droplet containing kerosene TS-1. The main properties of this component are as follows: density 780 kg/m$^3$, kinematic viscosity $1.82 \times 10^{-6} m^2/s$, ash content 0.003 %, flash point 301 K, ignition temperature 345 K, temperature of boiling 433-453 K, combustion heat 43.12 MJ/kg. These values was measured according with the techniques described in [8]. The initial volume of water in emulsion droplets ranges from 4.5 µl to 17 µl. The initial volume of kerosene - from 2.5 µl to 14 µl. The initial radius of water droplets is 1.03-1.6 mm. The initial radius of oil product droplets is 0.85-1.5 mm.
2.2. Experimental setup

Figures 1 and 2 illustrate schemes of the experimental assemblies utilized. As you can see the W/O and O/W emulsion droplets are heated on the substrate and in the hot airflow. The substrate is a steel plate of 5 mm in thickness and 20 mm in diameter having the cavity of 6 mm in diameter and 2 mm in height. This cavity is a place for arrangement of the emulsion droplet. The air blower and heater provide for the stream of hot air which flows inside the hollow quartz cylinder. The emulsion droplet are introduced in this cylinder through the 10-mm hole.

![Figure 1. Scheme of experimental setup with heating in the hot air flow.

To measure temperatures of the substrate and air inside the cylinder, we utilize the type-S thermocouples with the measurement range of 233-1773 K, accuracy of 1.5 K, junction thickness of 0.05 mm and response time not more than 0.1 s. To collect the measurement readings, we apply the data acquisition device National Instruments NI 9219.

The method of the high-speed recording is applied to study the vaporization process. In particular, during the processing of the video data we analyze the evaporation time of the emulsion droplets. Error on determining of the evaporation time is 0.005 s. The well-known optical technique Particle Image Velocimetry (PIV) [9] enables us to control the air flow velocity in the cylinder. Errors on measuring of the air flow velocity by the PIV method do not exceed 0.05 m/s.

The introduction of the emulsion droplets into the cylinder is performed by using the minirobotic arm. Such the approach allows the precise adjustment of the position of the emulsion droplets in the recording area of the video camera. For experiments on the substrate, we use the electronic dosing device. This device takes the preliminary prepared emulsion droplet and arranges to the substrate heated to the required temperature.

We perform the four series of experiments for each configuration of the emulsion droplet. Each series includes 6-10 tests. Such the number of tests contributes to the satisfactory repeatability of the measurements. The failed measurements are excluded from the consideration. The deviations of the parameters under study are less than the systematic errors mentioned above.

3. Results and Discussion

Figures 3 and 4 illustrate the most desirable result of the intensive heating of the emulsion droplets. Note that the stages of heating-up, evaporation, boiling and explosive breakup of the emulsion droplets are implemented extremely rapidly within both the ways of heating.
Figure 3. Explosive breakup of the emulsion drop when heated in the hot air flow ($T_g \approx 773$ K).

Figure 4. Explosive breakup of the emulsion drop when heated on the substrate ($T_g \approx 773$ K).

We report the short description of a behavior of the processes under study according to the stages presented in Figures 3 and 4. Since the kerosene has low heat of vaporization versus water, then we observe its intensive boiling in the surface layer of the emulsion droplet. The vapor bubbles move toward the free surface of the emulsion droplet. Differences in surface tension of the droplet components and their viscosity lead to the deformation of the interfacial boundary between water and kerosene. Due to this we can monitor the enhancement of the water heating-up. Moreover, the heat transfer by convection and radiation is enhanced in the kerosene layer. This occurs due to the high emissivity of the oil product. Obviously, the kerosene absorbs more heat energy compared to the water. Consequently, the supply of the heat energy to the interfacial boundary increases. This results in the evaporation enhancement of both the kerosene at the free surface of the emulsion droplet and water on the interfacial boundary. Further, we observe the expansion of the emulsion droplet and its explosive breakup. Before the explosive breakup of the emulsion droplet we monitor, based on the thermocouple measurements, the considerable overheating of liquids above the bubble point. Based on the Kutateladze criterion, we establish the value of overheating for the kerosene-water emulsion droplet. This value is equal to 17-19 K.

Figures 5 and 6 present the research results within which the opportunity appears to predict the implementation of any mode of phase transformations when heated in the hot airflow. The findings in Figure 5 consider the variation of the volume concentration of kerosene in the emulsion droplets. According with the data in Figure 6, it is possible to define the particular mode of phase transformations of the emulsion droplets taking into account the speed and temperature of the heating medium, i.e. air. The experimental results allow us to distinguish the three regimes.
of the explosive breakup. These regimes differ by number and size of the liquid fragments produced during the breakup. Moreover, the times of heating until the explosive breakup are different.

The first regime is characterized by the several-fold difference between size of the droplets produced during the breakup. The range of droplets size is from 0.3 mm to 1.7 mm. The heating until the explosive breakup is up to six seconds. For the second regime the time of explosive breakup is characterized as a mean one among the three regimes. The size of the produced droplets varies from 0.15 mm to 0.9 mm. The explosive breakup within the third regime occurs during less than three seconds. The size of the liquid fragments produced ranges from 0.02 mm to 0.1 mm, but the number of these fragments is from several dozens to several hundreds.

Heating of the emulsion droplets on the substrate includes more modes, see Figure 7. We distinguish the four modes: evaporation, rolling or bouncing of the emulsion droplets, explosive breakup due to the expansion of the droplets, explosion during combustion. Figure 7 shows that when increasing the ratio between the radiant heat flux near the droplet surface $Q_{rad}$ and total heat flux $Q_{sum}$ when heated on the substrate, the enhancement of the phase transformations occurs. At high values of the ratio we observe the explosive breakup of the emulsion droplets.

The volume concentration of the oil product in the emulsion droplets and the heating temperature are the main parameters in the research. They define the regime of the explosive breakup and the lifetimes of the emulsion droplets. In particular, Figure 8 illustrates how the increase in volume concentration of kerosene in the emulsion droplets effects their lifetimes in the hot air flow.

The explosive breakup phenomenon of the emulsion droplets containing the oil products with different concentrations and properties contributes to the increase in the efficiency of the purification technologies of the contaminated water. The main benefits of implementing the phenomenon include the considerable increase in the surface area of phase transformations. The paper shows that the explosive breakup occurs when heated in the hot air flow and on the heated surface. It is suitable for the modern technologies of water cleaning at high temperatures.
Figure 7. Modes of phase transformations versus ratios between radiant and total heat fluxes near the water-kerosene emulsion droplet surface at different temperatures of heating on the substrate.

Figure 8. Lifetimes of the emulsion droplets versus air temperature; droplets volume $V_d = 15\mu l$; different colors of the curves designate a volume concentration of kerosene in the emulsion.
because the heating of liquids in various heating chambers can be performed on the heated metallic surfaces or during spraying of aerosol into the flow of combustion products or heated air, as well as into the flame.

4. Conclusions
1. The experimental findings expand the existing database on the evaporation and fast phase transformations of the W/O and O/W emulsion droplets under high temperatures.
2. The opportunity to explode the emulsion droplets on the heated substrate and in the hot airflow allows the reproduction of the known purification technologies of the polluted water.
3. The increase in the $Q_{\text{rad}}/Q_{\text{sum}}$ ratio leads to the explosive breakup of the emulsion droplet with a formation of fine aerosol.
4. The conditions for the different phase transformations of the emulsion droplets were analyzed. In addition, the three regimes of the explosive breakup phenomenon were established. We revealed the main parameters which define the regime of the explosive breakup and the lifetimes of the emulsion droplets: the volume concentration of the oil product in the emulsion droplet and the heating temperature. Also, this paper using photos of the processes under study shortly describes the behavior of the evaporating emulsion droplets when heated on the substrate and in the hot airflow.

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