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The influence of impurities in droplets of slurries, emulsions and solutions on their evaporation rates

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The results of experimental studies of the integral characteristics of the evaporation of water droplets with impurities are presented. The variable parameters are as follows: gas temperature (573−873 K), type of impurities (solid — aluminum oxide, titanium dioxide, clay, silt, sand, and table salt; liquid — transformer oil, alcohol), and mass concentration of impurities (0.5−5%). Ranges of changes in the mass evaporation rate of droplets of slurries, emulsions and solutions have been established depending on the thermophysical and rheological properties of droplets with impurities, in particular, on density, heat capacity, thermal conductivity, and thermal diffusivity. An approximation expression is obtained that illustrates in the dimensionless form the dependence of the droplet evaporation rate on thermal diffusivity. An approach to predicting the evaporation rate of droplets with known thermophysical and rheological characteristics of the compound is proposed.

Keywords: droplet, impurities, solutions, slurries, evaporation rate.

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During the last decade, the number of studies in the field of evaporation of droplets of solutions with various-type impurities tends to increase because of their widespread use in the following technologies: thermal and flame treatment of water (process and sewage wastewaters) [1], gas-vapor-droplet heat carriers [2], polydisperse fire extinguishing [3], fuel technologies [4]. Manufacturing activities in many industries give rise to great amount of wastewaters. Their compositions include organic and inorganic impurities, such as metals and their derivatives, particles of clay, silt and other solid inclusions, glycols, amines, methanol [5]. As a rule, wastewaters undergo thermal treatment using such techniques as evaporation (concentration of impurities), drying (spraying the liquid in hot air or flue gases), thermal oxidation („burning" of impurities) [6]. Besides the wastewater treatment, the problem of optimizing and controlling the characteristics of liquid droplet evaporation at high (above 500 K) gas temperatures is currently topical also in fire fighting. It was found out that the presence of ground impurities (clay, sand, silt, soil) significantly intensifies phase transformations of inhomogeneous droplets because of the fact that thermal conductivity and thermal diffusivity of impurities are higher than those of water [7]. Characteristics of the evaporation process were determined, for instance, the droplet size (ΔR) dependence on relative mass fractions of impurities (clay, silt, sand, soil) in droplets [7]. At present, in this research field there is a lack of experimental data on mass evaporation rates of fine-dispersed water droplets containing various impurities. This is caused by some factors hindering the conduction of experiments (the droplet size below 2 mm, high process reaction rates) and also by the evaporation rate dependence on a variety of factors (droplet size, component concentrations, liquid and gas temperatures, input heat flux, and heating procedure). It seems reasonable to determine the evaporation rates during high-temperature (573−873 K) heating of water droplets containing solid and liquid impurities.

In the experiments, a set of typical solid and liquid impurities were added to water. Table 1 presents the thermophysical characteristics (density, thermal conductivity, heat capacity, thermal diffusivity) of the impurities, as well as their particle sizes and mass concentrations. As the table shows, the values of the impurity thermophysical parameters vary in wide ranges. Impurities of different types were used in view of further generalization of the obtained experimental results and also revealing of mathematical dependences of evaporation rates of the slurry, emulsion and solution droplets on their thermophysical and rheological parameters. Using laboratory microscale „Vibra HT 84RCE" with the resolution of 10^{-5} g, the necessary impurity mass was determined; after that, the impurity was added to the vessel (tank) with tap water (GOST R 51232−98) and thoroughly stirred until homogeneous composition is obtained.

The experiments were performed at the bench similar to that described in [8]. Using a special-purpose dispenser, a flow of droplets $R_d \approx 1$ mm in radius was generated and then fed into a cylindrical channel (a heat-resistant cylinder 1 m in height and 0.2 m in inner diameter) containing kerosene combustion products. The combustion product speed in the experiments was controlled by measuring the air flowrate in the exhaust ventilation system and equaled about $U_g \approx 1.5$ m/s. The droplet size was measured by the „shadow photography"method [9] in different sections along the entire height of the cylindrical channel by using a mobile detection system based on the traversing indexing

Table 1. Thermophysical characteristics of the used impurities.

Type of impurity	Thermophysical characteristics at 293 K				Mass concentration % (size, μm)	Ratio between thermal thermal diffusivity and impurity thermal diffusivity, a_{mix}/a_{imp}
	Thermal conductivity λ, W/(m $\cdot$ K)	Specific heat capacity C, J/(kg $\cdot$ K)	Density ρ, kg/m^3	Thermal diffusivity a, 10^{-8} m^2/s		
Titanium dioxide	0.599	720	4235	22.95	0.5 (0.1–2)	1.003
Clay	7	840	2750	6.49	1 (10–20)	0.995
Silt	1.5	1200	1050	14.2	1 (300–800)	0.999
Sand	1.8	960	1440	8.68	1 (100–200)	0.996
Graphite particles	1.2	710	1300	21.66	5 (20–30)	1.025
Transformer oil	2	2100	820	5.8	2.5	0.985
Ethyl alcohol	1	1000	987	7.09	5	0.975
NaCl	0.7	3200	1128	1.43	5	0.955

mechanism [8]. The „shadow photography" technique implies background illumination of the measurement area with a laser (in our case, green YAG:Nd-laser „Quantel EverGreen 70") by using an optical waveguide connected to a diffusing screen, and also video recording of the droplet images by using CCD video camera „ImperX IGV-B2020M". The experimental data was processed by using program code „Actual Flow". With the aid of special program filters, droplet boundaries were distinguished, noise was removed, and droplet radii were determined. The R_d determination error did not exceed 1.5%. In addition, the time required for droplets to pass through the channel with combustion products (Δt_d) was determined experimentally by tracking individual droplets with high-speed CMOS video camera „Phantom MIRO M310" (image resolution of 1280×800 px, frame rate of up to $6.5 \cdot 10^5$ fps). Time moments of entering (t_1) and exiting (t_2) the channel by the droplets were detected. The Δt_d determination error did not exceed 0.03%.

In the experiments, temperatures of air and combustion products (T_g) were detected using a measurement setup consisting of high-speed analog-input card „National Instruments" of the NI 9219 type and four chromel-alumel fast-response thermocouples located at four points uniformly arranged along the cylindrical quartz channel; the temperature measurement range of the thermocouples was 273–1473 K, systematic error was ± 3 K, and thermometric lag was shorter than 0.1 s. The maximal random errors in measuring T_g did not exceed 15 K.

The evaporation rate in each experiment and for each liquid compound (see Table 1) was calculated as follows [8]:

$$W_e = \rho_d(R_d - R_d^*)/\Delta t_d = \rho_d \Delta R/\Delta t_d,$$

where ρ_d is the water density [kg/m^3], R_d and R_d^* are the initial and final values of the droplet radius [m], Δt_d is the time of droplet passing through the channel containing combustion products [s]. The error in determining the droplet mass evaporation rate was maximum 2.5%. where ρ is the density [kg/m^3], λ is the thermal conductivity [W/(m $\cdot$ K)], and C is the specific heat capacity [J/(kg $\cdot$ K)].

Fig. 1 presents the revealed dependences of the droplet evaporation rates ($R_d \approx 1$ mm) on their rheological and thermophysical characteristics (density, specific heat capacity, thermal conductivity) for different values of the initial temperature T_d of the liquid ranging from 293 to 373 K under the condition of feeding the droplets into the counter-directed combustion-product flow $T_g = 573$ K in temperature. The analysis of data presented in Fig. 1 has led to a conclusion that the evaporation process undergoes a joint influence of three above-mentioned characteristics. Hence, studying the influence of only one of those three parameters on the evaporation is incorrect. Therefore, it is reasonable to generalize the considered parameters in the form of one physical quantity, namely, thermal diffusivity that characterizes the rate of the substance temperature variation in unsteady thermal processes. Thermal diffusivity was calculated as

$$a = \lambda/(\rho C),$$

Fig. 2 demonstrates the dependences of relative mass evaporation rates of the liquid droplets ($R_d \approx 1$ mm, $T_g \approx 573$ K) on their relative thermal diffusivity for three initial temperatures of the liquid; the dependences were obtained from calculations. The relative mass rate of evaporation and relative thermal diffusivity were calculated as

$$W_e' = W_e/W_e^{\max}, \qquad a' = a/a_{\max},$$

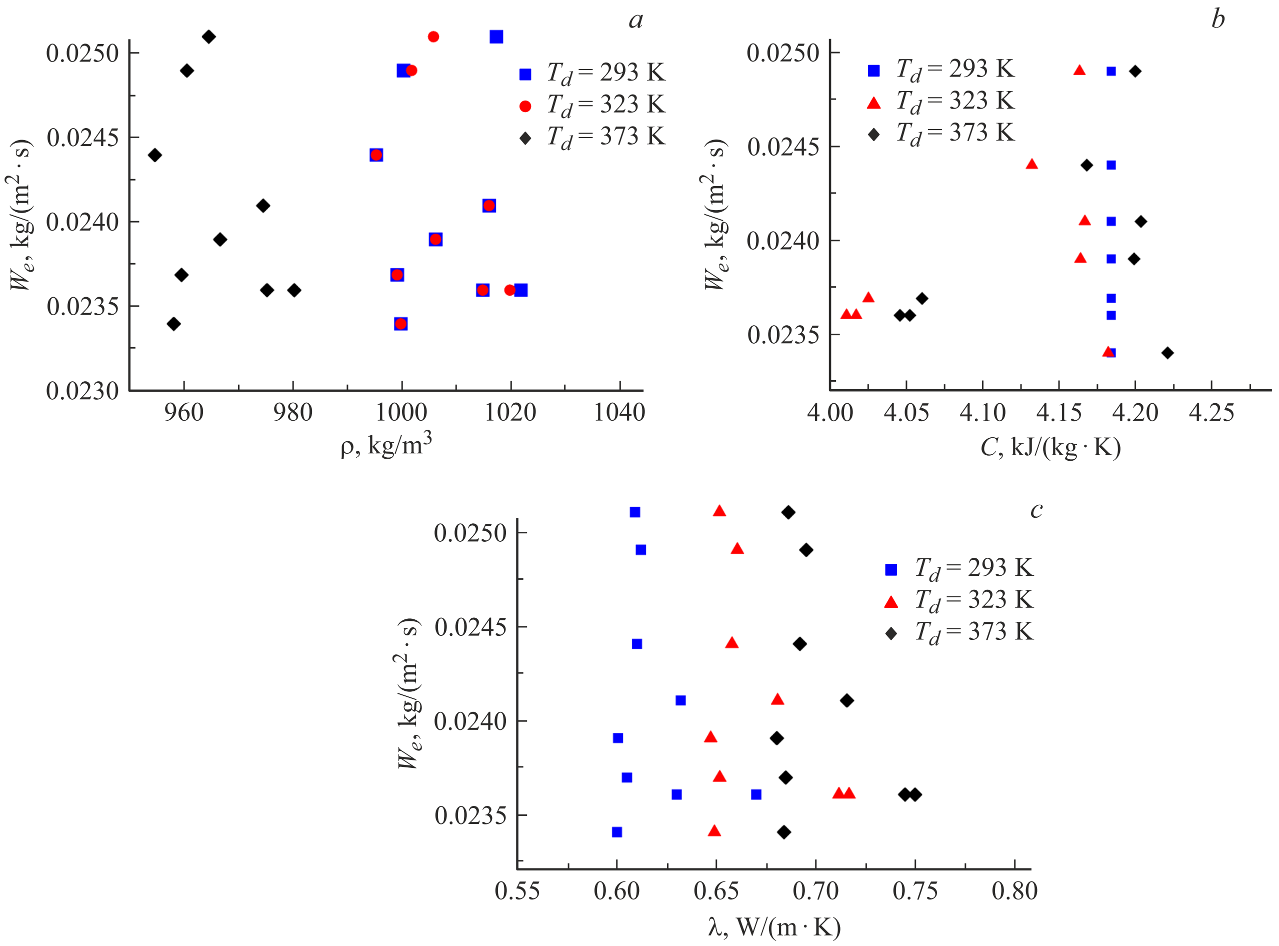

Figure 1. The effect of rheological and thermophysical characteristics of the investigated liquid compounds ($R_d \approx 1$ mm, $T_g \approx 573$ K) on the droplet mass evaporation rate for different initial temperatures of the droplets (293–373 K).

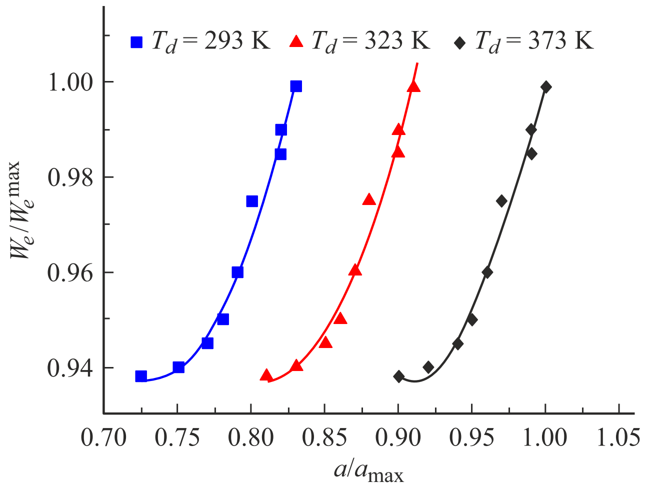

Figure 2. Relative mass evaporation rates of droplets of the compounds under study ($R_d \approx 1$ mm, $T_g \approx 573$ K) versus their relative thermal diffusivity for three initial temperatures of the droplets. The lines represent approximations for each temperature.

where $W_e^{\max}$ and $a_{\max}$ are the maximal values of parameters W_e and a, respectively, derived from the experimental results. As Fig. 2 shows, the characters of the evaporation rate variation dynamics at all the three considered initial temperatures are comparable. Under similar conditions (heat flux, combustion product temperature, initial droplet temperature and radius), the increase in the compound thermal diffusivity due to adding impurities to it results in an increase in the evaporation rate of droplets during spraying. Analysis of Fig. 2 has shown that one and the same value of the evaporation rate can be achieved by increasing either the dropletsínitial temperature or thermal diffusivity. The obtained result is of a great applied importance. For instance, knowing the concentration (mass fraction) and type of the impurities contained in the liquid, it is possible to calculate the temperature to which the liquid should be heated to reach the maximal evaporation rates. Provided the water temperature is fixed, the impurity concentration and type necessary for obtaining the required evaporation characteristics may be predicted. Thus, controlling the phase transition characteristics of the liquid becomes possible, which is, evidently, very important for a wide range of practical applications.

Table 2. Function $W_e' = b + c\exp(da')$ coefficients

Initial temperature of the droplets, K	Coefficients of the approximating function			R^2
	b	c	d	
293	0.9346	$1.21 \cdot 10^{-1}$	27.05	0.9636
323	0.9647	$5.06 \cdot 10^{-18}$	21.58	0.9999
393	0.9176	$3.24 \cdot 10^{-9}$	17.07	0.9908

By approximating the experimental results (Fig. 2), a generalized mathematical expression for predicting the dependence of the liquid-droplet mass evaporation rate on its thermal diffusivity was obtained for three initial temperatures:

$$W_e' = b + c\exp(da').$$

The coefficients of the obtained approximating function W_e' are given in Table. 2. The conducted experiments allowed us to establish that evaporation rates of droplets of solutions with impurities during their spraying in a high-temperature gaseous medium depend mainly on their thermophysical parameters, namely, on thermal diffusivity. Along with this, it has been shown that by varying such parameters as the impurity concentration and type, as well as the liquid temperature, it is possible to quite successfully control the liquid evaporation characteristics.

Notice that the phase transformation rates depend also on the impurity characteristics: particle concentration and size (for solid impurities). If the droplets contain solid impurities, there are observed active absorption and accumulation of the combustion product energy, and, hence, intensification of heating and evaporation of droplets. This is caused by that in this case the amount of energy needed to heat the slurry droplet surface layer to the state of active evaporation is lower. In addition, moving droplets with impurities exhibit more intense deformation than those of impurity-free water. This leads to more intense agitation of the liquid layers and increase in the mean droplet temperature. Hence, since in the process of preparing the solid impurity sizes (Table 1) cannot be strictly equal to each other, and their variation within a certain range is observed, even more intense heat exchange between the liquid layers occurs. In paper [9], it was justified that, in the case of an insignificant water vapor content, the droplet temperature during evaporation reaches a steady value which is lower than the flow temperature by hundreds of degrees. This phenomenon produces a kind of thermal protection of the droplet against the ambient gas (a buffer vapor layer).

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Conflict of interests

The authors declare that they have no conflict of interests.

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