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# Experimental investigation of mixtures and foreign inclusions in water droplets influence on integral characteristics of their evaporation during motion through high-temperature gas area

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ABSTRACT

Experimental investigation of influence of mixtures and foreign inclusions in water droplets on integral characteristics of their evaporation during the motion through high-temperature (more than 1000 K) gas area has been held. Investigations have been conducted with the usage of two-phase and heterogeneous mixtures diagnostics optical methods “Particle Image Velocimetry” and “Interferometric Particle Imaging”. It has been established that salt admixtures injection with sufficiently large relative concentration ($\gamma = 0.1$) influences moderately on droplet evaporation characteristics (evaporation velocities are decreased by 5–7%) when water droplet sizes are less than 0.5 mm. Salt admixtures influence is intensified (evaporation mass velocities of water droplets with admixtures and without of them differ by 11–18% at droplet sizes 1–3 mm) with droplet size increase. It has been indicated that foreign solid particle injection in droplets leads to considerable (by several times) intensification of droplet heat-up and evaporation processes. The thermophysical characteristics of these foreign solid particles significantly differ from water. Conditions of significant deformation and breakage of water droplets with solid inclusions have been indicated at intensive evaporation.



## 1. Introduction

Droplet evaporation processes of different (primarily homogeneous in composition) liquids, in particular, water, emulsions on its base, liquid fuels and other are investigated actively [1–14] for many years in consequence of a large number of supplements in all industry segments practically. In recent decades the resource efficiency programs are realized in many developed countries. These programs supposed to optimize the technological process. That is possible only at total control of all these processes stages and using modern high-end technologies.

Thus, for example, attempts of high-end technology [15–20] creation with usage of fine liquids, gas-vapor-droplet flows and vapor-water mist was made in fire fighting field in recent years. The main attention is given to evaporation process intensification of extinguishing liquid in the flame zone and fire large area coverage. Liquids (water and emulsions on its base), using in fire fighting systems, in particular [15–20], can be significantly unhomogeneous in composition. They contain different admixtures and solid inclusions with thermophysical properties which are differed considerably from liquid in real practice. The assessment of the most typical admixtures and inclusions influence on integral characteristics of water droplet evaporation in flame and high-temperature (more than 1000 K) combustion product areas is expedient. Thus, for example, salt admixtures and different nonmetal inclusions can be marked for water, using in fire fighting systems [15–20]. At that, both sufficient large droplets (sizes more than 1 mm) and fine trickle flows (with droplet sizes from tens up to hundreds μm) are of interest.

Operation analysis [21–30] shows that the experiment methods of “tracer” visualization, for example, PIV (“Particle Image Velocimetry”) [31–33] and IPI (“Interferometric Particle Imaging”) [34] can be used to study the macroscopic regularities of such processes.

The purpose of this work is to investigate experimentally the typical salt admixtures and foreign solid inclusions in water droplets influence on integral characteristics of their evaporation in high-temperature gas flow.

## 2. Experimental setup and procedure

The experimental setup was used (similar to experiments [35–38]). It includes (Fig. 1) the cylinder from a heat-resistant

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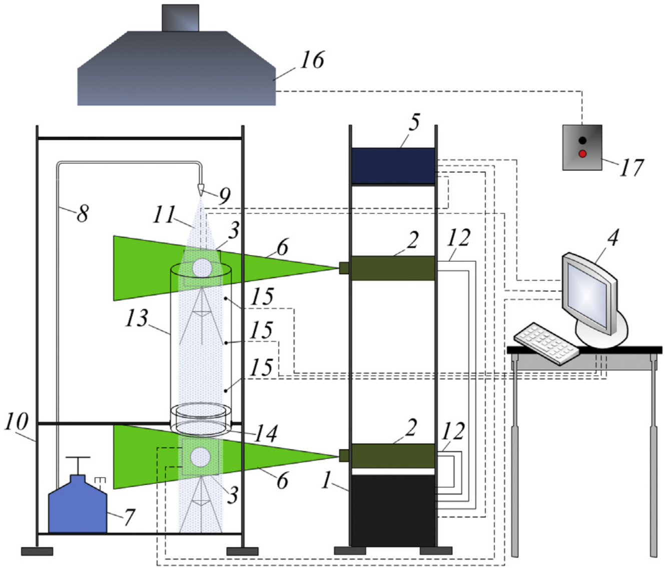


**Fig. 1.** A scheme of experimental setup: *1* – laser emission generator; *2* – double pulsed solid-state laser; *3* – cross-correlation digital camera; *4* – PC: personal computer; *5* – synchronizer of PC, cross-correlation digital camera and laser; *6* – light "pulse"; *7* – vessel with experimental liquid; *8* – channel of experimental liquid supply; *9* – atomizer (dosing device); *10* – tripod; *11* – experimental liquid droplets; *12* – cooling liquid channel of laser; *13* – cylinder from a heat-resistant translucent material; *14* – hollow cylinder; *15* – thermocouples; *16* – replacement exhaust system; *17* – control panel of replacement exhaust system.

translucent material *13* (height 1 m, diameter 0.3 m) and the hollow cylinder *14* (height 0.1 m, internal and external diameters – 0.26 and 0.3 m correspondingly) – for forming of high-temperature gas area; atomizer (dosing device) *9* – for generation of water droplets with intended sizes; recording equipment (cross-correlation digital camera *3* with figure format – 2048 × 2048 pix, frame frequency – not less than 1.5 Hz, delay between two sequence figures – not more than 5 μs; double pulsed solid-state laser *2* with active "yttrium aluminum garnet" sphere and neodymium additives, wave-length – 532 nm, energy in impulse – not less than 70 mJ, impulse time – not more than 12 ns, recurrence frequency – not more than 15 Hz; synchronizing processor *5* with signal sampling – not more than 10 ns) – for "keeping" track of water droplets in high-temperature gas area.

Water with special inclusions – "tracer" particles were used as an experimental liquid. "Tracers" are the admixture (relative mass concentration is 0.5%) of titanium dioxide nanopowder. The inclusions were added to increase the contrast of videograms which were received with cross-correlation digital camera. Nanoparticles of $TiO_2$ were chosen as a "tracers" because they are not dissolved in water [35–38]. Also nanoparticles of NaCl (relative mass concentration was changed in the range of $\gamma = 0$–$0.1$) and carbon particles with sizes $L_m = 50$–$500$ μm and concentration $\psi = 0$–$0.01$ were added in experimental liquid to investigate the typical admixtures and foreign solid inclusions influence on water evaporation characteristics. Investigations were conducted for single droplets with sizes $R_d = 1$–$5$ mm and their large aggregate with sizes $R_m = 0.05$–$0.5$ mm.

Characteristic sizes of carbon particles were measured before experimentations by using the microscope Hitachi TM-3000 (minimal measuring sizes are about 50 nm). Carbon particles which are differed in sizes from each other by not more than 5–7% were used in experiments.

Specialized many-level system of continuous mixing of contained liquid with specialized solutions was installed in vessel *7*. This system was activated after injection of foreign (carbon) particles (with required relative concentration) into the liquid.

Droplets with identical concentration of solutions which were well illuminated in experiments were selected at analysis of experiment videograms. Other droplets were excluded from consideration.

Intensive change of suspension droplet form (10–15 different configurations during motion in experimental channel with high-temperature gases) leads to continuous mixing of solution in droplet during its motion. Solid particles can not be accumulated in the droplet's bottom because of its continuous deformation under these conditions.

Even if leave out of account the processes of continuous droplet deformation during flight and suspension intermix, it can be analyzed the process of gravitation carbon particle settling into the droplet's bottom. Forces of gravity ($F_1$), Archimedes ($F_2$), friction ($F_3$) and resistance ($F_4$) act on the particle during flight. Equation of particle motion in the droplet is as follows:

$$m_p \frac{dV_p}{dt} = \sum_{i=1}^{4} F_i \ \text{ or } \ m_p \frac{dV_p}{dt} = F_1 + F_2 + F_3 + F_4.$$

Particle velocity at the initial time moment (at injection of droplet into high-temperature gas area) is $V_p = 0$ m/s and it can be noted:

$$F_1 = F_2 + F_3. \qquad (1)$$

We insert (1) the expressions for these forces and receive:

$$m_p g = m_w g + S_p k_{fr} P.$$

After substituting the parameters corresponding to the conducted experiments, we see that $F_3 >> F_1$. So carbon particle settling onto "bottom" of droplet during its flight with low velocity (to 5 m/s) is improbable.

It should also be noted that inertial forces oriented (as measured by videograms of experiments) in all three coordinate directions and conditioned by three-dimensional deformation of a droplet in flight, impact on carbon particles in flight too. If "settlings of particles" is formed in the bottom of droplet then this effect would be well exerted on videograms of experiments (but these effects were not recorded). So this effect can be excluded from consideration during the analysis of experiment results.

Liquid droplet concentration (during experimentations with atomized flow) in high-temperature gas area was assumed in sufficiently narrow range 0.001–0.0012 $m^3$ of water droplets/$m^3$ of gas in consequence of the limitations of "tracer" visualization optical PIV [31–33] and IPI [34] methods (using at experiment processes).

Each experiment included two series of ten experiments. At first series video frames of water droplets at the inlet of cylindrical channel *13* with high-temperature gases (Fig. 1) were fixed. At the second series droplet images were registered after their passing the channel *13*.

Each series of experiments was foreseen some stages:

- the vessel *7* was filled in by liquid with intended content of admixtures and inclusions;
- the dosing device (atomizer) *9* was connected to the outlet of the vessel *7* and was tuned according to necessary parameters of droplet generation;
- the vessel *7* with the atomizer *9* was installed on the tripod *10* at 0.5 m above the top facet of cylinder *13* (required removal due to the necessity of atomizer *9* protection against the melting at the impact of high-temperature gases which get out the cylindrical channel *13*);