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Experimental determination of water droplet "strain cycles" characteristic in the gas area

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Abstract. Experimental investigation of deformation regularities of widely used in industry liquid (water, kerosene, ethanol) droplets during the motion through the gas area under the action of gravitational forces has been conducted. Droplet characteristic sizes were varied in the range from 3 mm to 6 mm. Droplet motion velocities were come up to 5 m/s. Cross-correlation video recording system with optical methods of droplet size and velocity measurement was used. More than 10 characteristic droplets "strain cycles" have been established during they pass the distances up to 1 m through the gas area. The characteristic droplet forms, times, extents and amplitudes have been determined for each "strain cycle". The expression has been formulated which describes the characteristic "strain cycles" time dependencies on droplet velocities and sizes, also on the fundamental properties (viscosity, density, surface tension) of liquid and gas area in a first approximation. The conditions of droplet deformation intensification and this process in industry gas-vapor-droplet setups stabilization have been determined.

1. Introduction

"Oscillating modes" [1–5] regularities of droplet movement in liquids allow carrying the inference that process of droplet movement represents a fixed sequence of "strain cycles", which are characterized by fold repetition of their forms. In many cases "time intervals between the nearest compatible phases of oscillating droplets deformation" means the characteristic times of "strain cycles" τ_d. The attempts of expression developments were made according to physical liquid properties and the droplet sizes for times of τ_d. The analysis of experimental investigations [6–9] dedicated to studying of breakage and coagulation processes for droplets of various liquids in a gas flow, allows carrying the inference that droplet movement velocities may influence rather significantly on characteristics of their deformation. The assessment of this factor influence on deformation conditions of droplets of liquids widely used in various supplements is of interest. Characteristic times of droplet deformation at We $>$ 10 are negligibly owing to intensive breakage and atomization. These are embarrassing sufficiently significantly the analysis of "strain cycles" realization regularities. Values We $= 7 - 9$ are adduced as Weber's maximum permissible numbers in [7–9].Therefore, it is expedient to choose sizes and movement velocities of liquid droplets proceeding from We $<$ 7 condition.

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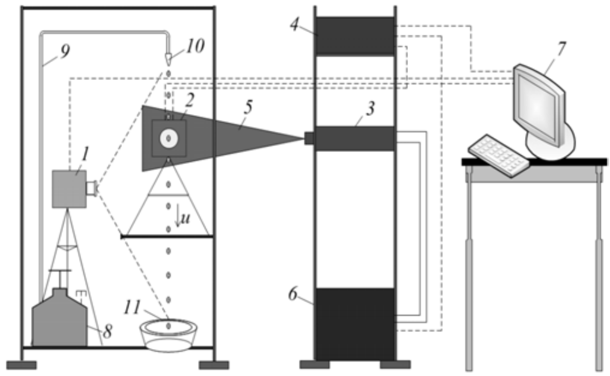

Figure 1. A scheme of experimental setup: *1* – high-speed digital camera, *2* – cross-correlation digital camera, *3* – double pulsed solid-state laser, *4* – synchronizer of personal computer (PC), cross-correlation digital camera and laser, *5* – light "pulse", *6* – laser generator, *7* – PC, *8* – vessel with experimental liquid, *9* – channel of experimental liquid supply, *10* – dosing device, *11* – catcher.

The purpose of the work is an experimental definition of the main characteristics of droplet "strain cycles" during movement in gas area.

2. Experimental setup and methods

The scheme of the experimental setup is presented in Fig. 1. The setup is similar to that one which are applied at investigation carrying out of water droplet evaporation in high-temperature (more than 1000 K) gas area [10–12] with using of "Particle Image Velocimetry" (PIV) and "Interferometric Particle Imaging" (IPI) [13–15] methods. The main elements of the stand are similar to applied in [10–12]. The digital camera *1* (with format – 1024 × 1024 pixels, the frame frequency – 100 000 per second) was used for droplets registration in the experiments opposite to techniques [10–12].

Experiments were conducted as following manner. Liquid from vessel *8* on the channel *9* arrived to the dosing device *10* inlet. Single droplets which flew through video registration area in air to a catcher *11* emanated from the dosing device *10* according to the defined initial d_0 sizes and u_0 velocity. Process of droplet movement was registered by the digital camera *1*. Not less than 10 experiments for detented sizes and velocities of droplets (under other fixed conditions) were conducted. Sections with characteristic changes in droplets configuration were determined after processing of videograms on the personal computer (PC) *7*. The distance between dosing device *10* and catcher *11* was broken up into group of the sections characterizing the respective "strain cycles", and measurements of time τ_d and s_d dimension were carried out at processing of the digital camera *1* records. The initial sizes of water droplets were varied in the range of 3–6 mm. The diameter (d_0) of droplet at a separation from the dosing device *10* was accepted as its initial characteristic size. Initial droplet velocities u_0 were varied within the range from 0 to 3 m/s.

The main parameters characterizing "strain cycles" were calculated: d_x – maximum transverse (relative to the movement direction) size of the droplet, mm; d_y – maximum longitudinal size of the droplet, mm; d_{max} –absolute maximum size of the droplet, mm; the dimension of cycle s_d, mm; time of cycle τ_d, s. Changes during measurement of d_x, d_y and d_{max} relative to the value of d_0($\Delta x = (d_x - d_0)/d_0$, $\Delta y = (d_y - d_0)/d_0$, $\Delta_{max} = (d_{max} - d_0)/d_0$) were calculated.

The scaling coefficient S was estimated according to recommendations [13–15]. Relative maximum diameters of droplets in pixels were calculated with using of basic algorithm procedures [13–15] and techniques [10–12]. After that the recomputation of the characteristic droplet size in millimeters was

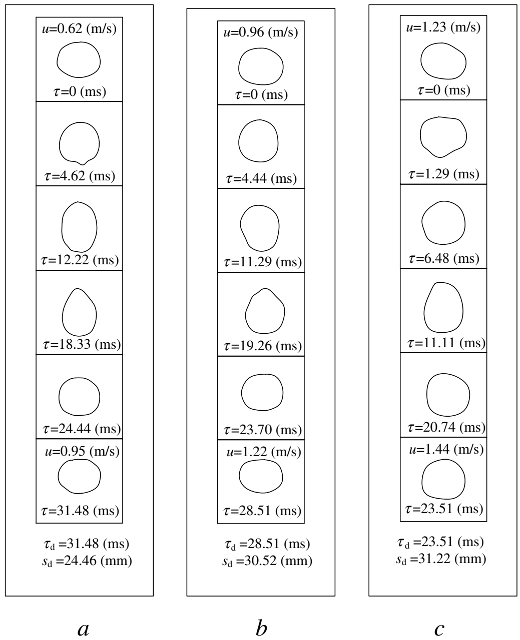

Figure 2. Images of ethanol droplet ($d_0 = 4$ mm) during several "strain cycles" at free falling: *a* – the first cycle, *b* – the second cycle, *c* – the third cycle.

performed at known coefficient S. Systematic errors of the droplet size measurement were not more than 0.01 mm.

Droplets movement velocities u within the frame of each characteristic "strain cycle" were calculated from results of videograms processing at the fixed values of τ_d and s_d.

Experiments of direct u measurement with using of the optical PIV [13–15] method and techniques [10–12] were conducted to verify the velocity movement values u. Measurement of momentary velocity field is based on registration of "tracers" movement in the fixed time interval (100 nanoseconds according to techniques [13–15]). Processing of droplets video images containing "tracers", is based on the cross-correlation algorithm representing the method of fast direct Fourier transform with using of the correlation theorem [13–15] execution condition. Momentary velocities of "tracers" [13–15] were defined at known delay times between flashes of the laser and the most probable particle movements in video frame computational domains. Velocities of droplet movement u were calculated from "tracers" velocities similar to [10–12]. Systematic errors of droplet velocity measurement were not more than 0.01 m/s.

3. Results and discussion

Continuous variation of droplet forms during the whole time period corresponding to their movement from the dosing device to the catcher was established.

Typical images of ethanol droplets for several consequent "strain cycles" are adduced in Fig. 2. Video frames are assumed in the case of droplet free falling for the purpose of possible comparison with results of experimental investigations of such processes (in particular, [2]). Six characteristic forms were defined at sequence analysis of the video frames with water-glycerin dilution's droplet images [2]. Identical droplets forms were registered when digitalization of frames (within the frame of the first "strain cycle") in the executed experiments (Fig. 2a). Good correlation with [2] and time intervals

Table 1. Time of “strain cycles” according to the sizes and velocities of droplet movement.

u (m/s)	**1**	**2**	**3**	**4**	**5**
d_0, (mm)			**Kerosene**		
2.5	0.02961	0.02865	0.02772	0.02682	0.02595
3	0.03254	0.03123	0.02998	0.02877	0.02762
3.5	0.03676	0.03483	0.033	0.03126	0.02962
4	0.0398	0.03718	0.03474	0.03245	0.03032
4.5	0.04051	0.03781	0.03529	0.03293	0.03074

between the main forms, their sequence, and also geometrical singularities (in particular locations of droplets symmetry axis) should be noted. At the same time it is notedly that there are a lot of specific forms which weren’t registered in [2]. It was recorded between presented for the first “strain cycle” droplets forms (Fig. 2a).

Characteristic ranges (Δx, Δy, Δmax) of droplet deformation and the dimension (s_d) of the cycle weren’t described in [2]. Therefore quantitative comparison of experiment results with findings of [2] can be executed only by times τ_d. Every next “strain cycle” was differed in the main characteristics from the previous sufficiently significantly in the conducted experiments.

Values of τ_d and a number of specific droplet forms are decreased, and the s_d parameter is increased with every next cycle (Fig. 2). The marked features are coming from the droplet velocity u rise (Fig. 2 shows the values of droplet velocities at the “inlet” and “outlet” of cycle). Action of skin-friction and resistance forces increases under rising of u. The increase of the mass and inertial forces exerting on a droplet, leads to its deformation process intensification. This, in its turns, initiates the decrease of characteristic times τ_d and increase of s_d value. The values illustrating the influence of d_0 and u on time τ_d are provided in Table 1. The increase of droplet sizes leads to rising of their mass and, as a result, slows down the processes of form change – times τ_d are raised.

The established features of droplet movement velocities influence on τ_d times allow carrying the inference about significant restrictions on the use of expressions presented in [2], for calculation of the first “strain cycle” times:

$$\tau_d = \frac{\pi}{4}\frac{\rho_1\delta^2}{\eta_1}\frac{1}{\sqrt{\mathrm{Lp}}-6.25}, \qquad (1)$$

where ρ_l – liquid density, kg/m^3; δ – characteristic droplet size, mm; η_l – dynamic viscosity of liquid,kg/(m · s); Lp – Laplace’s number ($\mathrm{Lp} = \delta \cdot \rho_l \cdot \sigma_l/\eta_l^2$).

Approximating expressions for τ_d times, according to droplet velocities at the inlet into “strain cycle” and also the initial sizes were received. For example:

$$\tau_d = 0.0289 - 0.0023\,u \text{ at } d_0 = 4\,\text{mm}, 0 < u < 5\,m/s; \qquad (2)$$

$$\tau_d = 0.0376 - 0.0022\,u \text{ at } d_0 = 5\,\text{mm}, 0 < u < 5\,m/s; \qquad (3)$$

$$\tau_d = 0.0017d_0^2 - 0.0087d_0 + 0.0326 \text{ at } u = 2\,m/s, 3 < d_0 < 6\,\text{mm}; \qquad (4)$$

$$\tau_d = 0.0011d_0^2 - 0.0021d_0 + 0.0136 \text{ at } u = 4\,m/s, 3 < d_0 < 6\,\text{mm}. \qquad (5)$$

Approximations (2)–(5) are presented for τ_d times, according to velocity at the inlet into “strain cycles” and the initial size d_0. Velocity of droplets during the movement process increases nonlinear. Therefore, it is quite difficult to assume the τ_d, as function of $u = f(\tau)$. The account of $d_x = f(\tau)$, $d_y = f(\tau)$ and $d_{max} = f(\tau)$ dependences is of even great difficulty as a consequence of continuous deformation.

Experiments showed that the droplet has a spherical form not more often than the form of ellipsoid, “plate”, elongate cylinder and other rotation bodies (Fig. 2) in the process of deformation. Therefore,

Table 2. Middle experimental characteristic "strain cycles" times and the expressions calculated by using of (6).

d_0, (mm)	3	4	5	6
Experimental "strain cycles" times τ_d, (s)	0.02000	0.02578	0.03430	0.03960
"Strain cycles" times the expressions calculated by	0.01448	0.02338	0.03338	0.04448
using of (6) τ_d, (s)	0.01448	0.02338	0.03338	0.04448

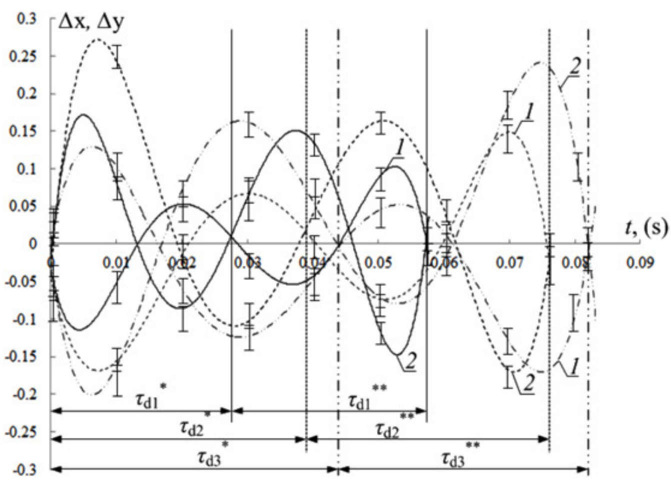

Figure 3. Values of Δ_x (*1*) and Δ_y (*2*) at $u = 1$ m/s and $d_0 = 4.5$ mm during two characteristic "strain cycles" of liquid droplets at whole time of their movement in the air about 70 ms (τ_d^* – the first of concerned cycles; τ_d^{**} – the succeedent cycle): (–) – water, (- -) – kerosene, (– ·· –) – ethanol.

it is expedient to calculate the S_d droplet area at the beginning of every "strain cycle" and consider its change in the cycle $S_d = f(\tau)$ for maximum possible approximation of expression (1) to real values of τ_d.

Values of τ_d may be calculated with the use of expression (1) at $u \to 0$ m/s. The first summands in formulas (2)–(5) are practically (deviations up to 7%) equal to the t_d values determined with the use of the expression (1) for corresponding characteristic droplets sizes d_0. The marked deviations may be reduced to $3 \div 4\%$ when using the values of the droplet areas at the inlet into "strain cycle" (S_d) determined according to real droplet forms instead of a multiplier $\pi\delta^2/4$ in expression (1).

The second summands in expressions (2)–(5) can be defined from expression $(\text{We}/(\text{Lp}–6.25))^{0.5}$. It was established as a result of iterative determines at $d_0 = 3 \div 6$ mm and $u = 0 \div 5$ m/s. In such a way, the formula for calculation of "strain cycle" times with consideration for droplets form, their sizes, movement velocities, properties of liquid and gas:

$$\tau_d = \frac{\rho_1 S_d}{\eta_1 \sqrt{Lp - 6.25}} - \sqrt{\frac{\text{We}}{Lp - 6.25}}. \tag{6}$$

Expression (6) can be used as a first approximation for the establishment of water droplets "strain cycles" times under concerned conditions. Deviations of the computed τ_d values from the experimental ones are less than 6% at average velocities of movement ($2 \div 4$ m/s). The experimental and calculated by using the expression (6) times τ_d for water with droplet velocity at the inlet into the "strain cycle" of 3 m/s are presented in Table 2. These deviations can be considered quite reasonable if the adduced confidential intervals (about 4%) will be considered. Deviations from experimental values of τ_d are sufficiently significant at "low" (about 1 m/s) and "high" (about 5 m/s) velocities at the inlet into "strain cycles". This result allows carrying the inference of expression (2) frontier by u velocities.

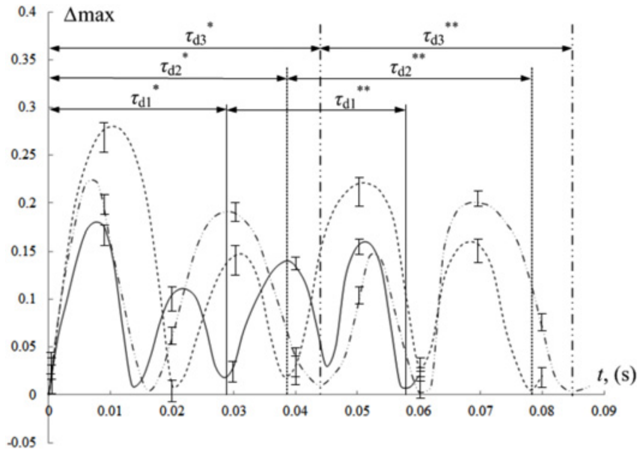

Figure 4. Values of Δ_{max} at $u = 1$ m/s and $d_0 = 4.5$ mm during two characteristic "strain cycles" of liquid droplets at whole time of their movement in air about 70 ms (τ_d^* – the first of concerned cycles; τ_d^{**} – the succeedent cycle): (–) – water, (- -) – kerosene, (– ·· –) – ethanol.

The amplitude variation (Δ_x, Δ_y and Δ_{max}) of concerned liquid droplet deformation during several "strain cycles" with relevant times τ_d are presented in Figs. 3 and 4. Asymmetry of change in droplet sizes in two coordinates of diagram flatness ($\Delta_x \neq \Delta_y$) should be noted. This is the basis for conclusions about dimensioned droplet deformation. Continuous variation of droplet form during sufficiently small time interval ($\tau_d \ll 1$ s) should be noted too. This result allows carrying the inference that it is incompletely soundly to use the approaches based on suppositions about the droplet form constancy (sphere, ellipsoid, elongated cylinder) at a numerical simulation of liquid droplet movement processes.

Differences of the main characteristics (Δ_x, Δ_y, Δ_{max}, τ_d) of "strain cycles" (Figs. 3, 4, Table 1) for water, kerosene and ethanol droplets at identical movement velocities and droplet sizes are due to distinction of these liquids physical properties. For instance, it was established that values of τ_d and s_d for water, kerosene and ethanol droplets are differed not more, than by 5%. The viscosities and densities of these liquids are sufficiently close (differences by 4–7%). Slight reduction of τ_d for kerosene droplets in comparison with ethanol may be explained by the fact that ethanol has the surface tension coefficient σ which is in 17–25% more than for kerosene. Parameter σ for water exceeds values of σ for kerosene and ethanol by two-three times.

It is also possible to draw the conclusion about sufficiently close values Δ_x, Δ_y and Δ_{max} for kerosene and ethanol, and also about smaller values of droplet water strain ranges in contrast with these liquids by comparison of strain ranges for droplets of concerned three liquids (Figs. 3, 4). The established regularity is also due to multiply large values σ of waters in comparison with ethanol and kerosene. The moderate influence of liquid viscosity and density on characteristic "strain cycles" times was established in experiments [2] with water-glycerin droplets (density was changed by 1.5 times, and viscosity on some orders due to increase of mass concentration of glycerin particles in water droplets).

4. Conclusions

The main characteristics (τ_d, s_d and Δ_{max}) of "strain cycles" are sufficiently significantly changed during motion of investigated liquids through the gas area. This is mainly due to the increase of droplet movement velocities u. The number of characteristic droplet forms in every next cycle is decreased at the increase of droplet movement velocities u. It was established that known [2] expressions for the main characteristic of "strain cycle" (τ_d) can be used only at $u \ll 1$ m/s. Expression (6) can be used, as a first approximation for the predictive analysis of t_d times at velocities of liquid droplet movement in the air, changing in the range of 0–5 m/s.

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