Interfusing Processes Visualization of Unequigranular Water Droplets Flow and High-Temperature Gases Flow at the Conditions of Intensive Phase Change

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Abstract Experimental method was developed and experimental researches were executed for investigation processes of polydisperse water droplets flow and high-temperature gases stream at the conditions of intensive phase change. PIV and IPI methods of panoramic optical visualization were used. Integral characteristics of water droplet deformation and coagulation at it counterflow moving through a high-temperature (more than 1000 K) gases were established. Some modes of droplets deformation and mechanisms of it coagulation were defined. Rates of high-temperature water evaporation were calculated. Velocity of vapors outflow from an evaporating surface was established. The prognostic model of high-temperature evaporation of water droplet flows in a gaseous area was developed.
Keywords: water droplet, high-temperature gases, evaporation, deformation, coagulation, PIV, IPI

1 Introduction

Water droplets are one of the most extensively studied subjects in the field of heat and mass transfer, evaporation, interaction liquids and gases. Processes of droplets deformation, heat and mass transfer and phase transitions during water droplet motion through high-temperature gas areas are of the utmost interest because of many [1–4] supplements (for example, power stations with gas-vapor coolants, fire suppression systems by “water mist” and “vapor-water” clouds, techniques of granular medium defrosting and different materials surface processing by gas-vapor-droplet flows). Such processes for high-temperature (over 1000 K) gas areas [1–5] are in a special interest. But it is very difficult to find integral characteristics of water droplets deformation and coagulation at its moving through high-temperature gas area without usage of high-speed measurement technique, for example [5-7].

The purpose of this work is an experimental study of interfusing processes of unequigranular water droplets flow and high-temperature gases flow at the conditions of intensive phase change.

2 Experimental setup and methods

The scheme of the experimental setup is shown in Fig. 1. This facility is an improved version of the setup used in previous experiments and described in the references [4, 8, 9]. The major change is the integration of a high speed video cameras *1, 2* (frequency up to 10^5 frames per second) able to record positions and shapes of single droplets and of polydisperse water droplets flowing in high-temperature gas stream. The basic equipment is: cross-correlation cameras *3, 4* with a chip resolution - 2048×2048 pixels (minimum delay between two picture recordings shorter than 5 µs), double pulsed solid-state laser *18* (with with active “yttrium aluminum garnet” sphere and neodymium additives, wavelength 532 nm, an impulse energy of at least 70 mJ, impulse duration of maximum 12 ns, recurrence frequency not more than 15 Hz); synchronizing processor *17* with 10 ns signal sampling. The utilization of a high speed camera allowed a detailed and accurate description of the kinetic of the deformation of evaporating droplets falling in a column of gas at different temperatures.

The water with special inclusions – “tracers” was used as atomized water. That was an admixture (0.5% by weight) of titanium dioxide nanopowder. The “tracers” were added for videogram contrast increase (similar as in [8, 9]). The atomizing device *12* [8, 9] was used for generation of water droplet aggregate with constrained initial sizes. The average condition radius R_{m0} (similar as experiments [8, 9]) was chosen as a characteristic droplet size, because the water droplets took the form of ellipsoids [10] during motion through the gas flow as a rule. The initial droplet sizes R_{m0} were set in the range of 0.01–0.5 mm when the appropriate settings of atomizing device *12* were changed (Fig. 1). The initial atomized water droplet velocities were varied in the range $0.1<U_{m0}<5$ m/s at pressure setting in vessel *11*. The relative concentration of water droplets in gas flow was assumed in a narrow range 0.001–0.0012 m3 of water droplets / m3 of gas in terms of limitations (upon the minimal number of droplets and "tracers" in videogram registry space) of optical methods (IPI) and (PIV) [11–13].

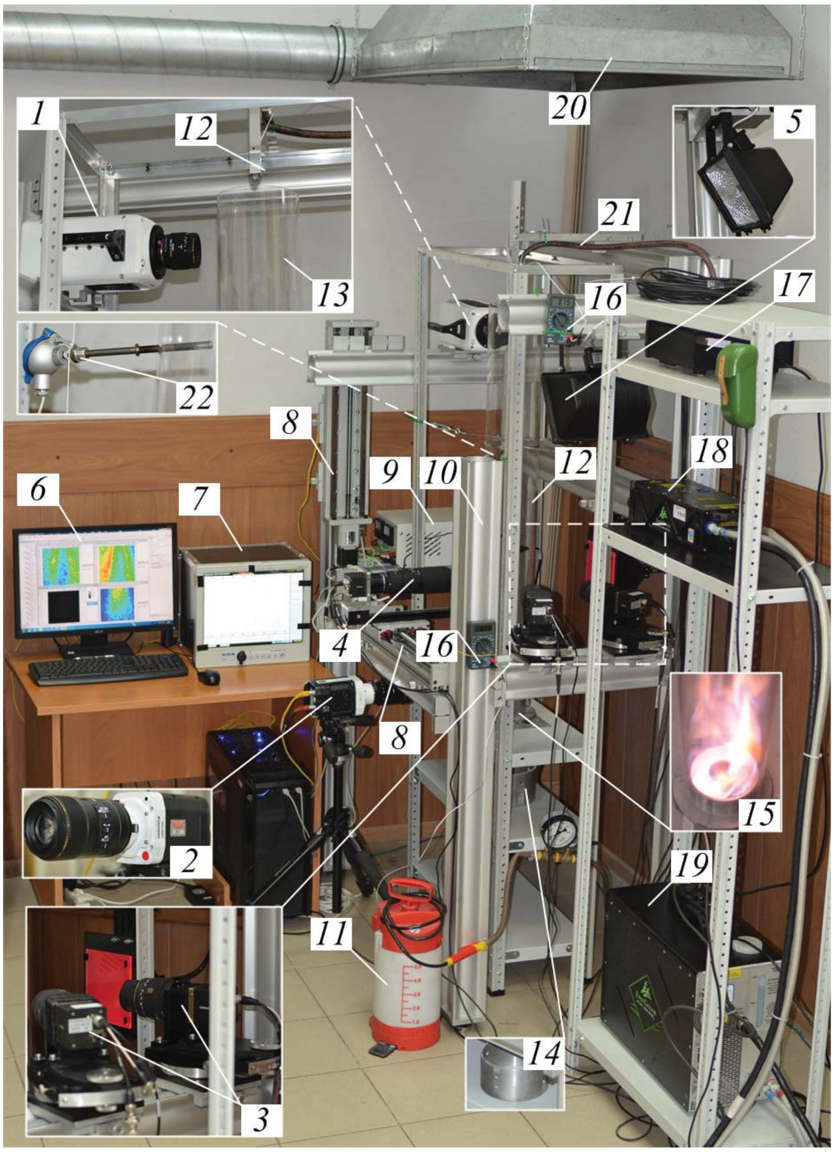


Fig. 1. Experimental setup: *1, 2* – high speed video cameras; *3, 4* – cross-correlation digital cameras; *5* – lighting searchlight; *6* – personal computer (PC); *7* – technological multichannel registrar; *8* – motorized coordinate device (MCD); *9* – MCD power supply unit; *10* – aluminum rack; *11* – vessel with water; *12* – atomizing device; *13* – cylinder of quartz glass; *14* – droplets catcher; *15* – the hollow cylinder with combustible liquid; *16* – digital multi-meter; *17* – synchronizer of PC, cross-correlation digital camera and laser; *18* – solid state lasers for ultrashort pulses; *19* – laser generator; *20* – replacement exhaust system, *21* – channel of water supply; *22* – thermocouples

The ΔR parameter was added under review. This parameter characterized the modification of water droplets during motion through high-temperature gas area relatively to its initial condition radius R_{m0} ($\Delta R=(R_{m0}–R_m^*)/R_m$, where R_m^* – the value of droplet average condition radius at channel with high-temperature gases *13* outlet, mm).

The procedure of experimentation was similar to [8, 9]. The specialized positive pressure system *11-12* (Fig. 1) was used to vary the initial velocities of water droplet aggregate injection in channel *13* in range typical for large supplements group (in particular [1-7]).

Before each test kerosene was set on fire at the base of cylindrical channel *15* similar to experiments [8, 9]. The gas (combustion products) temperature in channel *13* reached the values 1070±30 K in 5 minutes. Thus, the high-temperature gas area with controlled key parameters was formed.

The gas velocity in channel *13* was varied in the range $0.1<U_g<2$ m/s by the external pressure regulation with an extraction system *20* usage. High-temperature gas velocities distributions in the channel *13* were determined by PIV method [11, 12] from "tracers" movement velocities.

For creation of a polydisperse droplet flow as the atomizing device the set of the specialized metallic atomizing nozzles was used (Fig. 2). It allowed to change the initial size (R_{m0}) of the sprayed water droplets in the flow in the wide range: from 0.01 to 0.5 mm.

Fig. 2. Used in experiments atomizing devices

Water droplet velocities distributions were determined by PIV method [11, 12]. Water droplet sizes in the videograms registration spaces (before and after high-temperature gas area) were determined by using the optical IPI method [13].

Gas temperature T_f in the cylindrical channel *13* was controlled by chromel-alumel thermocouples *22* (Fig. 1) at different height levels (0.15 m, 0.5 m, 0.85 m) and was 1070±30 K. The initial temperature of water was controlled by chromel–alumel thermocouples at two points (in the vessel *11* and on an entrance of the atomizing device *12*) with using of digital multi-meter *16* and was 298±1 K.

Fractional errors of measuring devices of "tracer" velocities did not exceed 2 % [8, 9], droplet sizes – 1.5 % [8, 9]. Random measuring errors of these parameters came up to 2–3 %. To decrease these errors form 7 to 10 experiments were conducted under identical initial conditions.

3 Experimental investigation results

Fig. 3 shows typical videogram and velocity field at mixture of a polydisperse droplet flow and stream of high-temperature gases.

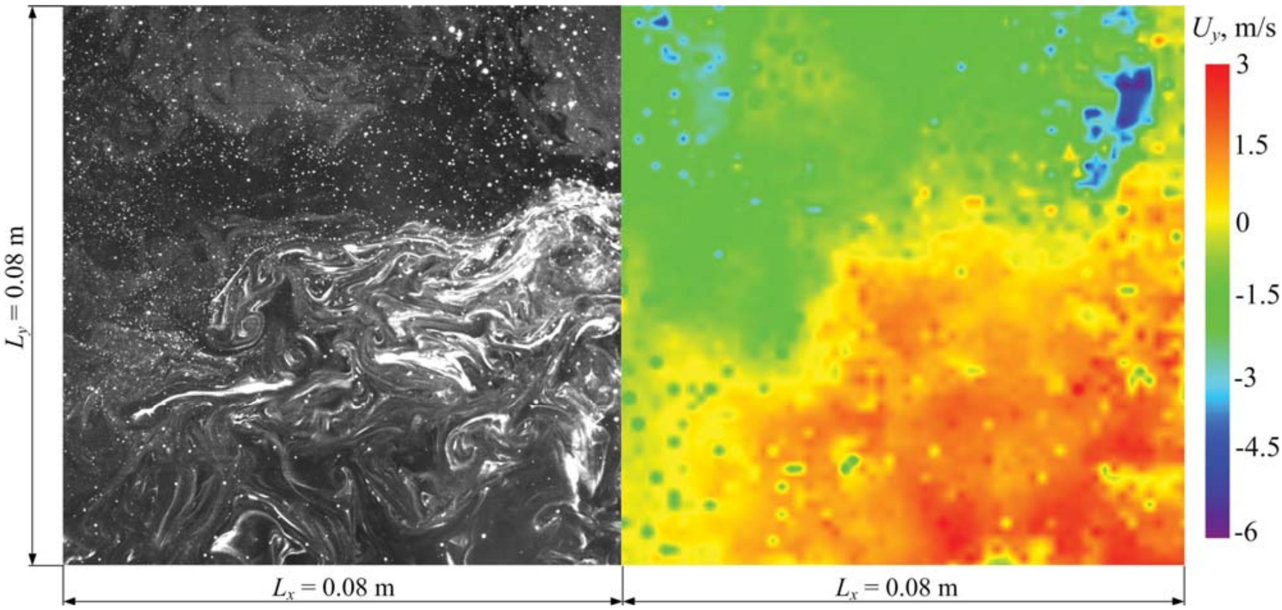
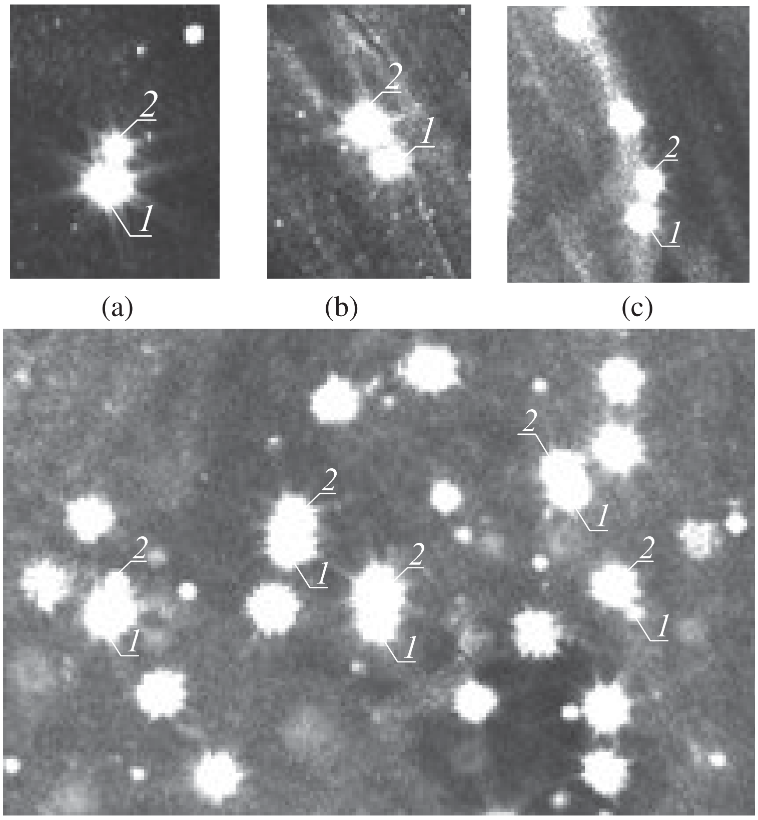


Fig. 3. The videogram and velocity field at mixture of a polydisperse droplet flow and stream of high-temperature gases

The executed experiments showed that the defining role at mixture of gaz-vapor-liquid streams on an entrance to a flame zone (Fig. (3)) is played by the phenomenon of coagulation (merge) of liquid droplets (Fig. 4). This phenomenon is observed between the droplets having, as a rule, various sizes, velocities and even the directions of the movement in a gas stream.

Proceeding from results of experiment, it is possible to allocate two main mechanisms of emergence of the phenomenon of droplets coagulation. The first (Fig. 4 (a)): the stream of the leaving gases promotes braking ahead of the going water droplets, to their turn and the subsequent merge to the liquid droplets going opposite. The second (Fig. 4 (b)): droplets, getting to turbulences of a high-temperature combustion products stream, follow in its current and merge among themselves. The last statement visually illustrates also Fig. 4 (c), in where the group of four droplets which got to turbulences of the leaving gases stream gradually merges in some joint structure.



(a) (b) (c) (d)

Fig. 4. Illustrations of the phenomenon of droplets coagulation (*1, 2* – the first and second merging droplets) at various mechanisms of its realization: (a) – braking of the droplet going in front and its merge to the subsequent; (b), (c) – droplets merge at the passing movement in turbulences of high-temperature gases; (d) – chaotic merge of drops at their big concentration in a stream

It should be noted that manifestation of coagulation effect significantly depends on droplets concentration in the sprayed liquid flow. So, at rather small concentration of drops of liquid their merge has casual (almost single) character (Fig. 4 (a)–(c)). With increase of water droplets concentration in registration area absolutely opposite picture is observed (Fig. 4 (d)) – merge of drops becomes not accident any more, and it is rather a regularity. Thus both are realized described above the coagulation mechanism.

Features of change of water droplets movement trajectories on an entrance to a flame zone are analysed. The trajectories of water droplets with sizes R_{m0}=0.3÷0.4 mm were practically unchanged in concerned high-temperature gas area. It is necessary to provide the liquid dispersion when the inequality R_{m0}>0.16 mm will be accomplished to realize the preservation conditions of initial trajectories of water droplet movement in channel of high-temperature gases with corresponding U_g. It has been established by the usage of received videograms and velocity fields (in particular, shown in Fig. 2 and 3). At the same time it has been found that above 85 % of water droplets evaporate during motion through high-temperature channel *13* in length 1 m if characteristic droplet sizes are 0.175<R_{m0}<0.275 mm. Droplets with sizes

R_{m0}<0.175 mm evaporate completely. Series of performed experiments showed that droplets with initial sizes 0.16<R_{m0}<0.175 mm are not “whirl away” by gases and evaporate almost completely in channel *13*.

At the same time small droplets (R_{m0}<0.16 mm) are “whirl away” by gases and die away with other droplets which move after them (Fig. 2). As a consequence it is its motion direction modification. And united droplets return partially (15–20 % of the total number of droplets with the initial characteristic sizes 0.2≤R_{m0}<0.5 mm as a rule) in high-temperature channel *13*. Experiments showed that these processes realize cyclically.

The evaporation features of the sprayed water droplets at the movement through a counter flow of high-temperature gases are also established. So, it is established that droplets with R_{m0}=0.25÷0.4 mm evaporate for 20-30%, droplets with R_{m0}=0.15÷0.25 mm - for 30-60%, droplets with sizes (R_{m0}) less than 0.15 mm evaporate almost completely.

Analysis of the videograms of the performed experiments (similar to Fig. 3) makes it possible to come to the conclusion that in the process of movement through the gas medium, the drop shape changes only slightly. Respectively, the deviations in the integral parameter, ΔR, for the identical initial conditional radii, R_m, are within 1.5%. So, the drop shape does not in fact influence the liquid evaporation intensity. The result obtained makes it possible, when modeling the process considered, to neglect the possible deformation of the flying drops and the deviation of their shape from the sphere (in particular, within the short times of movement in the gas flow). As a result of the analysis of the ΔR parameter a number of the mathematical models (given in [14]), allowing to predict the rates of high-temperature water evaporation (W_e) and the velocity of vapors outflow from an evaporating surface were written.

On the basis of the analysis and generalization of the experimental results obtained, we might make a conclusion on the asymptotic character of variation of the water evaporation rate at ambient temperatures sufficiently above the boiling temperature. On the condition of intensive vaporization in the wall zone of the liquid drop, its vapor concentration is so high that further increase in the external medium temperature does not influence essentially the drop surface temperature. Thus, the evaporation rate varies insufficiently as against the values with respect to the boiling temperature.

4 Conclusion

As a result of conducted experimental investigations with using optical methods (PIV and IPI) of gas-vapor-droplet mixtures diagnostic and also given mathematical models it was established that high-temperature gas flow exercises a decisive influence on vaporization intensity and coagulation of water droplets. Some modes of droplets deformation and several mechanisms of it coagulation were defined. Rates of high-temperature water evaporation were calculated. Velocity of vapors outflow from an evaporating surface was established. The prognostic model of high-temperature evaporation of water droplet flows in a gaseous area was developed.

Acknowledgements

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