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Experimental investigation of consecutive water droplets falling down through high-temperature gas zone

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ABSTRACT

An experimental investigation of the motion of water droplets falling down in series of 2, 3 and 4 through high-temperature gas (about 1100 K) was carried out. Sizes of droplets (radii 1–3 mm), initial distances between them (4–36 mm), initial speeds (0.5–2 m/s), as well as up-flow gas velocities (1.5 m/s) are varied within ranges corresponding to some advanced applications. Velocities and evaporation rates of each droplet were measured by high-speed video camera “Phantom” (up to 10^5 frames per second), associated with the software packages “Tema Automotive” and “Phantom Camera Control” while varying the distance between droplets within wide range. Conditions for coalescence of droplets, their slowing down and acceleration in high-temperature gases were determined. Influence of the initial droplet sizes, the distance between droplets, their temperatures as well as their number during motion in an upstream flux of high-temperature gases on the intensification of evaporation was analyzed. One of the most typical mechanisms of droplet coalescence in high-temperature gas zone was experimentally confirmed.

1. Introduction

High-temperature (more than 1000 K)[1] gas–vapor-droplet technologies are considered to be promising from already many years did not reach a development allowing intensive and wide applications [1–7] (see e.g. purification, fat extraction, special coating sputtering and complex structure dyeing by gas–vapor-droplet mixtures; scrubbing of thermal loaded surfaces of power equipment; defrosting of granular mediums by gas–vapor-droplet streams; energy-efficient heat carriers based on furnace gases, water droplets or emulsions and water vapors; thermal or flame purification of water, emulsions and suspensions on its base; polydisperse firefighting by steam–water aerosols; spray-technologies of droplets ignition of liquid fuel compositions). This is mainly due to the lack until recently of approaches and methods to validate laboratory investigations of the interrelated heat and mass transfer, evaporation and chemical reactions for gas–vapor-droplet systems.

Over the past few years panoramic optical methods, cross-correlation complexes, systems of high-speed photo and video recording allowed obtaining unique experimental results and detailed concepts about large groups of gas–liquid systems (films, droplets, bubbles, aerosols, two-phase, multiphase and heterogeneous fluxes) [8–15]. The non-intrusive optical methods are particularly noteworthy, e.g. especially “Particle Image Velocimetry” (PIV) [16–18], “Particle Tracking Velocimetry” (PTV) [19,20], “Stereoscopic Particle Image Velocimetry” (Stereo PIV) [21,22], “Interferometric Particle Imaging” (IPI) [23,24] and “Shadow Photography” (SP) [25,26]. These accurate metrology methods allowed obtaining new information about gas–vapor-droplet mixtures during intensive vaporization and chemical reactions (for example, [27–30]).

One of the main objectives to study gas–vapor-droplets flows is to measure and control concentration of droplets, particles, bubbles, vapor and components under different conditions of heat transfers, e.g. like in applications [1–7]. The results presented in the review work [31] demonstrate that droplets coalescence is one of the factors determining the concentration of droplet in multiphase flows. The mechanisms of coalescence and the main laws governing this process attracted attention of researchers [27–31]. The role of droplet coalescence is also important for gas–vapor-droplet high-temperature fluxes due to the corresponding intensification of heat exchange. The analysis of videograms of experiments allowed obtaining velocity fields of droplets free falling in high temperature gas [27]. By using PIV, Stereo PIV and PTV methods we obtained that droplet moving first in a row change significantly the heat exchange with gas of all the following droplets (i.e. droplets moving in front influence velocities, evaporation, the intensity of this interaction depends on sizes of droplets

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[1] In this report “high temperature” means between 1000 K and 1100 K.

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Nomenclature

A	dimensionless coefficient describing relative droplet acceleration
B	dimensionless coefficient describing the influence of droplet evaporation on resistance force
C_w	heat capacity of water, J/(kg K)
c_χ	dimensionless resistance coefficient
g	acceleration of gravity, m/s^2
k_g	dimensionless geometry coefficient characterizing the deviation of shape from spherical of the streamlined body
L_d	distance between centers of mass of droplets moving consecutively, mm
L_{d0}	initial distance between centers of mass of droplets moving consecutively, mm
R_d	radius of droplet, mm
R_{d0}	initial radius of droplet, mm
ΔR	decrease of droplet size relatively to initial one due to evaporation in high-temperature gas medium ($\Delta R = (R_{d0} - R_d)/R_{d0}$)
Re	Reynolds number
t	time, s
t_d	time of droplet motion in the channel with high-temperature gases, s
T_{ds} and T_{gs}	temperature of water and a mixture of combustion products and water vapor near the interface on the droplet surface, K
T_g	temperature of gas, K
T'_g	temperature of combustion products after passing a cloud of spray water droplets, K
ΔT_g	parameter reflecting the temperature reduction of combustion products after passing a cloud of spray water droplets ($\Delta T_g = T_g - T'_g$), K
T_w	temperature of water, K
U_d	speed of droplet motion, m/s
U_{d0}	initial speed of droplet motion, m/s
U_e	linear velocity of vapor outflow from the droplet surface ($U_e = W_e/\rho_g$), m/s
U_g	speed of gas motion, m/s
S_d	distance covered by a droplet in a reversed high-temperature gas flow to conditions of complete deceleration, m
V_d	volume of a droplet, μl
Q_e	thermal effect of liquid vaporization, J/kg
q_i	heat flow to a droplet, W/m^2
We	Weber number
W_e	evaporation rate, kg/(m^{2}s)
ρ_w	water density, kg/m^3
ρ_g	density of a gas mixture (the mixture of water vapor and combustion products), kg/m^3
σ_w	water surface tension coefficient, N/m
μ_w and μ_g	dynamic viscosity of a liquid and a gas–vapor mixture, kg/(ms)

and distances between them). A similar proposal was made based on the results of numerical simulation of motion of droplets moving consecutively through high-temperature gas (resulting from modification of temperature fields and concentration distributions of gases and vapors around droplets and in their trace) [32,33]. However, we did not yet find any experimental explanation about this interesting feature in droplet group with evaporation [32,33]. It has not yet been proposed conditions (droplet sizes, distances between them in gas, heat flux and etc.) for which this mechanism appears. But the effects of coalescence of droplets consecutively moving through gas at high temperatures are particularly interesting. Our present first step toward the understanding of this feature by measurements on small groups of droplets (for example, two, three and four droplets) seems fruitful. The conditions of heat exchange correspond to the gas–vapor-droplet of real applications (see particularly [1–7]).

The purpose of the present work based on our experiment results is to understand and to derive the main laws describing the consecutive motion of some water droplets falling down through combustion products at temperatures of about 1100 K, these conditions correspond to a wide group of advanced gas–vapor-droplet technologies.

2. Experimental setup and procedure

Experiments were conducted in the setup used previously [30] and which is presented on photo in Fig. 1.

The facility is integrated around high speed video cameras 1 “Phantom V411” and “Phantom Miro M310” (frame frequency – up to 10^6 fps). The software “Phantom Camera Control” and “Tema Automotive” capable to continuous tracking [34–36] were used to process and analyze the data recorded by video. In the present work we investigated the consecutive motion of a small number of water droplets (two, three and four). This approach is different from our previous experiments [30]. A dedicated and original device (called DRS for drop release system) was developed which is able to simultaneously release droplets. It allows studying droplets falling down consecutively with different imposed initial velocity through high temperature zone.

Experimental procedure included the following steps:

- Flammable liquid (200 ml kerosene) inside the burner 14, ignition of kerosene was initiated and then the quartz cylinder 13 is connected with burner 14.
- After 200 s (necessary time to heat the inside of cylinder 13 up to requested temperature). Water from the bottle 4 was taken out by dosing device 5, which generates droplets of fixed volumes and then places them on the needles of the DRS 11.
- DRS has a series of fixation points for needles located at nodes of a square network. The distance between nodes is 4 mm. Such step change in the initial distance between two droplets was selected based on their initial sizes (radii 1–3 mm) and simulation results [32]. The study [32] showed that the influence of each droplet going ahead on the evaporation conditions of subsequent ones is noticeable, when the distance between them is not more than several droplet diameters. In the channel with high-temperature gases, the distance between droplets less than 4 mm resulted in their quite uncontrolled fusion during falling. Therefore, it was important to determine the distance, which ensured good repeatability of experimental results. The number of installed needles is equal to the number of droplets necessary for the particular step to realize. Each needle then receives a drop of water. This drop has a controlled volume imposed by a precision electronic micropipette adjustable between 10 and 100 μl by step of 0.1 μl. The droplets can be simultaneously released by a sharp horizontal impulse of the needles support activated by a spring system.
- The droplets can fall down in a row or in parallel trajectories separated by distance adjustable by step of 4 mm as selected by the experiment definition.