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Water droplet deformation in gas stream: Impact of temperature difference between liquid and gas

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ABSTRACT

Experimental investigations were conducted to study the macroscopic behaviors of water droplets (diameter from 3 mm to 6 mm and velocities from 0.5 m/s to 5 m/s) deformed during falling down in a gas stream. Various temperatures of gases (275–1100 K) and water droplets (275–360 K) were considered. The investigations were conducted by using optical cross-correlation technics to measure the displacement velocity of droplets and the liquid convection as a function of time. High-speed (10^5 frames per second) video camera allowed to record the shape deformations. Two deformation modes were identified. The relationships between the shapes of droplets, their velocities and sizes were established. The impact of the temperature difference across the liquid–gas interface on the deformations characteristics was accurately analyzed. The main deformation properties (amplitude, length and period of one shape oscillation cycle) were evaluated at different temperatures of the surrounding gas and of the droplets; the velocities and sizes of droplets were measured and correlated with the shapes of droplets and their periods of oscillation.

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. In particular, it exists numerous publications which are devoted, for example, to the investigation of droplet formation [1–6], their deformation, breakage, coagulation, collisions [7–13], and evaporation [14–21]. The results of theoretical and experimental investigations published by now allowed to develop a large group of practical applications based on fluxes of liquid droplets; see Refs. [22–30]. The most typical applications are e.g. water in cooling towers of power plants, the high-temperature water purification at power engineering facilities, desalination of sea water, the defrosting of granular media by gas–vapor–liquid flows, the cleaning of slaggy surfaces of power engineering equipment by gas–vapor-droplet mixtures, the heat carriers exhausted from furnace gases, aqueous vapors and water droplets, the polydisperse vapor–water fire extinguishing.

The processes of droplet formation (separation from the outlet injectors of atomizers and spray devices) play dominant role in all these applications. The review [31] published practically all the main results of the investigations around these processes. It can be noted that the investigation of the concerned processes [31] were completed. The typical shapes of droplets and their formation modes were identified. It was not paid enough attention to the study of droplet shape modifications during their displacements through a gas stream after leaving the nozzle of injectors. Experimental [32–34] and theoretical [35–37] investigations showed that these processes may influence significantly the heat and mass transfer conditions in the droplet/gas stream system. The investigation of water (the most widely used liquid) droplet deformation when changing their velocities, sizes, initial temperature and temperature of surrounding gas in wide ranges are of interest in typical applications and are reported in [22–30].

The analysis of experiments [31–34] allows concluding that there is no break-up of droplets (for typical liquids including water and emulsions) during transfer through the gas flow as long as the change of their sizes and velocities corresponds to Weber numbers less than about 10. Therefore, in our investigations both the velocities of droplets and their sizes are limited by this condition $We_m < 10$. The influence of velocities and sizes of droplets on the characteristics of their deformation was established [7]. However up to now the influence of temperatures of the gas stream and of the droplets on their deformation was not investigated. It was also not reported how important is this influence on the variation of velocities and sizes of the droplets. The consequence is that the role of temperature difference across the liquid/gas interface on

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Nomenclature

d_0	initial droplet diameter, mm
d_m	maximum droplet diameter, mm
d_x	cross-sectional droplet diameter, mm
d_y	longitudinal droplet diameter, mm
g	gravitational acceleration, m/s^2
Lp	Laplace number
l_d	length of cycle, mm
n_d	sequence number of droplet shape
Re	Reynolds number
S_d	droplet cross-section area, m^2
t_d	time of oscillations cycle, ms
t_{d01}, t_{d02}, t_{d03}, t_{d04}	times of strain quarter cycles, ms
T_g	initial gas temperature, K
T_w	initial water temperature, K
u	droplet velocity, m/s
u_0	initial droplet velocity, m/s
We	Weber number
We$_m$	maximum value of Weber number
γ	scale coefficient, mm/pixel
δ	droplet size, mm
Δm	the relative maximum amplitude of droplet deformation
Δx	the relative cross-sectional amplitude of droplet deformation
Δy	the relative longitudinal amplitude of droplet deformation
Δt	characteristic times of transitions from one droplet shape to another, ms
η	dynamic viscosity of liquid, kg/(m s)
ν	kinematic viscosity of gases, m^2/s
ρ_g	gas density, kg/m^3
ρ_l	liquid density, kg/m^3
σ_l	liquid surface tension coefficient, N/m
σ_w, σ_e, σ_k	surface tension coefficient of water, ethyl alcohol and kerosene, N/m
τ_d	the dimensionless time of shape oscillations cycle

the deformation of water droplets moving through a gas flow was not fully analyzed.

The purpose of the present paper is to report on results of dedicated experiments performed to investigate the influence of temperature difference across the liquid/gas interface on the deformation characteristics of water droplets in a gas stream during their displacements at moderate velocities.

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 [19–21]. The major change is the integration of a high speed video camera ***1***[1] (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 camera ***2*** with a chip resolution – 2048 × 2048 pixels (minimum delay between two picture recordings shorter than 5 µs), double pulsed solid-state laser ***3*** (with 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 ***4*** 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 video system records a single droplet motion in the gas stream along a distance of 1.2–1.5 m between the receiver and the nozzle (***11***) of the injection system used to produce liquid droplets with imposed velocities and sizes. The initial sizes (diameters d_0 at separation from the nozzle ***11***) of water droplets were varied in the range: 3–6 mm and the initial droplet velocities u_0 were varied in the range: 0–3 m/s. Droplet velocities u increased up to 5 m/s during their motion through the gas volume. The maximum Weber numbers in the experiments were $\mathrm{We}_m = u^2 d_0 \rho_g / \sigma_w \approx 5$ when maximum gas density was $\rho_g \approx 2$ kg/m^3, water surface tension coefficient $\sigma_w = 0.0589$–0.0719 N/m [31]. We foresee that with the condition $\mathrm{We}_m < 10$ the possibility of droplet breakage is extremely small [32–34].

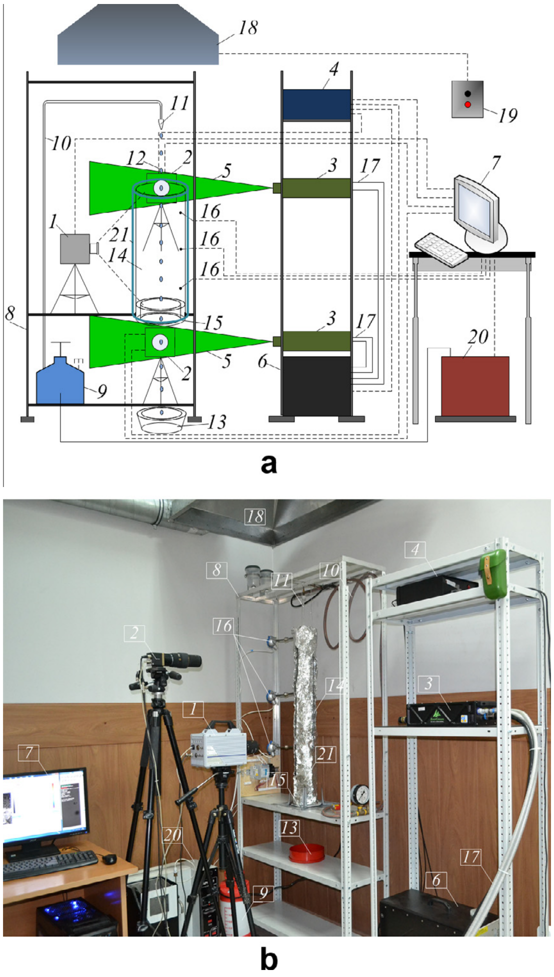

Fig. 1. The scheme (*a*) and photo (*b*) of the experimental setup: ***1*** – video camera; ***2*** – cross-correlation digital camera; ***3*** – double pulsed solid-state laser; ***4*** – synchronizer of PC, cross-correlation digital camera and laser; ***5*** – light impulse; ***6*** – laser emission generator; ***7*** – PC; ***8*** – tripod; ***9*** – vessel with water; ***10*** – channel of water supply; ***11*** – nozzle of dosing injecting system; ***12*** – water droplets; ***13*** – receiving vase; ***14*** – cylinder in transparent quartz; ***15*** – hollow cylinder with combustible liquid; ***16*** – thermocouples; ***17*** – supply of cooling liquid for laser; ***18*** – exhaust system; ***19*** – control panel of the exhaust system; ***20*** – heating setup; ***21*** – thermal insulating layer.

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[1] Refer to description in caption of Fig. 1.