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The integral characteristics of the deceleration and entrainment of water droplets by the counter flow of high-temperature combustion products

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ABSTRACT

This paper presents the results of experimental investigations on the deceleration and entrainment of water droplets during their motion in the counter flow of high-temperature combustion products (up to 1900 K). High-speed video cameras (10^5 frames per second), specialized software applications (with continuous tracking functions), as well as panoramic optical methods (Particle Image Velocimetry, Stereoscopic Particle Image Velocimetry, Particle Tracking Velocimetry, Shadow Photography) registered the processes under study. We used several typical oils, gasoline, kerosene, acetone, and industrial alcohol to generate combustion products with a controlled high temperature. The initial sizes (radius) of droplets and their velocities were varied from 0.05 mm to 0.35 mm and from 0.5 m/s to 5 m/s. The velocities of counter motion of combustion products were varied from 0.1 m/s to 2.5 m/s. In this paper we have also determined the characteristic trajectory length of the droplets of different sizes until their complete stop (and subsequent entrainment) in the counter flow of high-temperature gases. As a result of studies, we summarized the research results through the establishment of Weber and Reynolds numbers ranges for droplets and gases, when the full stop and entrainment of droplets may occur. This paper also covers a comparison of the characteristics of water droplet deceleration under the conditions of non-stationary (when the temperature of combustion products varies from 1900 K to 400 K in channel) and nearly stationary (when the temperature is 1100 ± 30 K) heat transfer. Thus, it has been found out that the values of these parameters correlate well (deviation did not exceed 7%) under such conditions (stationary and nearly stationary) during short heating (less than 0.5 s).

1. Introduction

The evaporation of water droplets, suspensions and solutions in various gases has been a subject of scientific interest during recent years. This is due to a rather wide range of possible applications and the great significance of basic research results in this area [1–12]. Previous reports [5,12] showed that it is quite difficult to determine experimentally the evaporation rates of droplets falling in gas, as well as the temperature of their surface (especially the temperature distribution over their cross-section). The main reason is the continuous movement and transformation of the "liquid–gas" interface (due to phase changes, and droplet surface deformation under the influence of aerodynamic forces). Thus, empirical approaches are often used (for example, in studies [13–18]) to determine the basic parameters of droplet evaporation. The authors of papers [13–18] accepted the assumption that all energy supplied to a droplet is consumed only for the implementation of phase transitions. The temperature does not change from the surface of the droplet to its axis of symmetry (i.e., a temperature gradient is small inside the droplet). A balance equation $Q_e W_e = \alpha (T_g - T_s)$ [18] is considered to be classic for the "liquid–gas" boundary. The heat transfer coefficient α is determined by a group of equations: $Nu = 2 + 0.6Re_1^{1/2}Pr_1^{1/3}$, as in reports [15–18]. These assumptions can simplify significantly the physical and mathematical models of the processes under study. This may explain the widespread use of empirical approximations [15–18] in many models of heat and mass transfer for evaporating liquid droplets (for example, in the paper [18]). However, evaporation rates obtained by taking into account such assumptions correspond to experimental data only within limited gas temperature ranges (generally up to 500 K). In particular, studies [12,19–21] demonstrated that these approximations are quite difficult to use for obtaining reliable evaporation rates (and other integral parameters of this process) at high gas temperatures (more than 1000 K). This is caused by a significant change in droplet velocities due to evaporation. Therefore, it is advisable to conduct experimental studies to obtain the database, which will help to formulate new models

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Nomenclature

L_d	the distance passed by drops before full braking, m
L_c	glass cylinder height, m
Nu	Nusselt number
Pr	Prandtle number
R_c	glass cylinder radius, m
R_d	droplet radius, mm
Q_e	thermal effect of evaporation, J/kg
Re_d	Reynolds number for droplet;
Re'_d	relative Reynolds number for droplet;
Re_g	Reynolds number for gas medium
T_g	initial gas temperature, K
T_s	droplet surface temperature, K
T_w	initial water temperature, K
U_d	droplet velocity, m/s
U_g	gas velocity, m/s
U_g^{lim}	limit velocities of the counter gas, m/s
U_x, U_y, U_z	components of droplet velocity, m/s
W_e	evaporation rate, kg/(m^2 s)
We	Weber number
α	heat exchange coefficient, W/(m^2 K)
ΔR	parameter characterizing the decrease in the droplet radius (relative difference between the value of R_d at the input and output of high-temperature gas environment)
ν_g	kinematic viscosity of gases, m^2/s
ρ_g	gas density, kg/m^3
ρ	liquid density, kg/m^3
σ	liquid surface tension coefficient, N/m

of heat transfer and phase transitions. Moreover, it is of particular interest to study the motion of evaporating droplets in the high-temperature gas flow. It is also worth noting that the appropriate experimental database is needed for the simulation of such droplets.

Generally speaking, it is possible to establish experimentally the integral characteristics of droplet motion during evaporation in high-temperature gases [12] using optical techniques of tracer visualization (for example, Particle Image Velocimetry (PIV) [22–24], Stereoscopic Particle Image Velocimetry (Stereo PIV) [25], Particle Tracking Velocimetry (PTV) [26], Interferometric Particle Imaging (IPI) [27], Shadow Photography (SP) [28]). In recent years these methods have been widely used [22–28] to study heat and mass transfer, hydro and gas dynamics in systems with films, microchannels, aerosols, mixtures, two-phase and multiphase flows. There are some research results, where these methods are used to observe high-temperature (more than 1000 K) gas–vapor droplet and heterogeneous flows (for example, results described in Refs. [12,29–31]). However, there are very few examples of such results. This is due to great difficulties in adapting optical tracer visualization techniques for complex (in structure and the concentration of components) gas–vapor droplet flows.

In recent years, some reports [12,29–31] established the existence (complete evaporation) times of water droplets (with the initial size from 50 μm to 5 mm), suspensions, emulsions and solutions in high-temperature combustion products (about 1100 K) using optical tracer visualization techniques (PIV, Stereo PIV, PTV, IPI, SP and others). In these works, the laws have been determined that explain the velocity changes of droplets during their evaporation in the high-temperature gas flow. The conditions have been formulated that correspond to the deceleration and entrainment of droplets by gases. It should be noted that our previous experimental studies [29–31] examined the processes mentioned above for the combustion products of typical liquid fuel with stable properties (kerosene). However, in gas–vapor droplet applications (in particular, which are outlined in works [5,11,12]), liquid fuels such as gasoline, kerosene, acetone, industrial alcohol, oil, and different petroleum products are widely used to generate high-temperature gases. The temperatures of combustion products may significantly exceed the temperatures of 1100 K considered in reports [29–31]. In order to summarize the research results on water droplet evaporation in high-temperature gases, it is of interest to carry out experiments using the combustion products of relevant flammable liquids. In real gas–vapor–droplet thermal technologies, the temperature of gases (combustion products) can be varied quite significantly in the height of channels (from thousands to hundreds degrees). Usually, channel length does not exceed 1–3 m. It is advisable to compare the integral characteristics of droplet deceleration and entrainment by gases under the conditions of non-stationary and nearly stationary heat transfer discussed in papers [29–31].

The aim of the present paper is to determine the integral characteristics of water droplet deceleration and entrainment by the counter flow of the high-temperature combustion products of widely used flammable liquids.

2. Experimental setup and methods

Fig. 1 shows the photo of the setup used in our experiments.

The main tools of the setup were similar to that we used in previous investigations described in the paper [29]. The cross-correlation complex was based on a synchronizing processor *17* (maximum signal sampling 10 ns), and a double-pulsed Nd:YAG laser *18* (wavelength 532 nm, maximum pulse energy 74 mJ, maximum pulse duration 12 ns, repetition rate 15 Hz). Unlike the facility used in our previous studies [29], here we introduced two CCD cameras "IMPERX IGV B2020M" *3*, *4* (2048 × 2048 pixel aspect ratio, frame rate 1.5 Hz, minimum delay between two consecutive frames 5 ms), and two high-speed CMOS cameras "Phantom V411" *1* and "Phantom MIRO M310" *2* (1280 × 1280 pixels image format, maximum frame rate $6 \cdot 10^5$ fps). Fig. 2 shows cameras used in our experiments.

In order to implement the Stereo PIV method, it was necessary to install two high-speed CCD cameras. CMOS cameras were used to record the dynamics of drip flow motion through the counter-flow of high-temperature combustion products, as well as to control the distances passed by water droplets.

Unlike the experiments [29–31], to estimate the size of water droplets, the SP method was applied. Also, the cross-correlation complex was additionally equipped with a diffusion screen (Fig. 3). The screen was connected to the Nd:YAG laser *18* through an optical fibre. The screen was used as a backlight for falling water droplets, and was placed in front of the CCD camera *4* behind the drip flow (cylinder *14*). For laser illumination of droplets with the required parameters (intensity, the scattering angle), special diffusers (lenses) were put at the connection point between the optical fibre and the screen.

The methodology of the experiments (as in [29]) included the following steps:

– a container *11* was filled with preliminarily prepared liquid (with known characteristics) for subsequent spraying;