International Journal of Multiphase Flow 91 (2017) 184–193

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Gas temperature in the trace of water droplets streamlined by hot air flow

G.V. Kuznetsov, P.A. Strizhak*, R.S. Volkov, I.S. Voytkov

National Research Tomsk Polytechnic University, 30 Lenin Avenue, Tomsk, 634050, Russia

ARTICLE INFO

Article history:
Received 11 June 2016
Revised 9 December 2016
Accepted 5 February 2017
Available online 9 February 2017

Keywords:
High-temperature gases
Water droplet
Clay particle
Flowing around
Evaporation
Temperature trace

ABSTRACT

In order to obtain the knowledge necessary for developing new effective fire extinguishing technologies, we determined experimentally the gas temperature in the trace of water droplets streamlined by hot air flow. It was important to establish how much the temperature in the droplet trace decreases and how fast it recovery to the initial temperature field after the droplet evaporation. The following parameters were varied: droplet size from 1.3 mm to 1.7 mm, velocity from 1 m/s to 5 m/s, initial airflow temperature from 473 K to 773 K, number of droplets (one or two), and the arrangement of droplets relative to the hot inflow (serial or parallel). The study proves the theoretical hypothesis about a significant influence of evaporation on the temperature in the water droplet trace. When a temperature trace of water droplets is formed, irrespective of their arrangement, the role of the evaporation process strengthens with the gas flow temperature rising. Furthermore, the study specifies typical longitudinal dimensions of the aerodynamic and temperature traces of water droplets. It has been established that when droplets are located in series and in parallel, their combined impact on the temperature and velocity of the gas flow in the medium differs rather considerably.

1. Introduction

Aerosol flows consisting of water as well as water-based emulsions and suspensions are widely used in high-temperature (1000 K) gas-vapor-droplet applications (Sazhin et al., 2011; Avdeev et al., 2012; Varaksin, 2013; Hernández-Bocanegra et al., 2013). In particular, they are used for defrosting granular media; treatment of thermally loaded surfaces of power equipment; heat or flame water purification; production of water-based coolants, flue gas, and water vapor; and in gas-vapor-droplet extinguishing systems. One of the key issues in choosing the parameters for these technological processes remains a reliable forecast of the temperature and concentration of droplets and water vapor (Sazhin et al., 2011; Avdeev et al., 2012; Varaksin, 2013; Hernández-Bocanegra et al., 2013). They reflect some important energy and economic indicators of the science-intensive technologies listed above. The main detriment to the development of such technologies is the lack of knowledge (very few reliable experimental data) about complex heat transfer processes and endothermic phase transitions that take place during the motion of droplets and water vapor in a high-temperature gas environment.

The most widespread droplet evaporation models for a gaseous medium are diffusion models based on Maxwell's assumptions (Spalding, 1955; Fuchs, 1959) as well as kinetic models assuming that all the energy supplied to the liquid-gas interface is used up on vaporization (Ranz and Marshall, 1952; Yuen and Chen, 1978; Renksizbulut and Yuen, 1983). The main outcome of long-term attempts to develop these models is the database of empirical equations $\mathrm{Nu} = f(Re,\mathrm{Pr})$ (Terekhov et al., 2010).

These diffusion and kinetic models consider a limited number of heat and mass transfer processes between a drop flow of liquid and a gas environment (Terekhov et al., 2010). Thus, it is quite challenging to forecast the speeds of water droplet evaporation at high heating temperatures (over 600 K) using $\mathrm{Nu} = f(Re,\mathrm{Pr})$ empirical equations. For instance, Vysokomornaya et al. (2016) establish that, at high temperatures, the deviation between theoretical and experimental data may reach 60–80% (sometimes, these values may differ several-fold). Hence, the question remains (Corradini et al., 1988; Eckhoff, 2016) of creating heat and mass transfer models to obtain adequate temperature patterns at the near-surface layer of liquid droplets evaporating at high temperatures with the vapor cloud being formed. It is important to solve these problems, because they have a stifling effect on the high-performance technologies using water aerosols in high-temperature gas and vapor-gas systems.

* Corresponding author.
E-mail address: pavelspa@tpu.ru (P.A. Strizhak).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2017.02.002
0301-9322/© 2017 Published by Elsevier Ltd.

Recent studies (Strizhak et al., 2016; Volkov et al., 2016) specified the characteristic velocities of vaporization when heating water and typical water-based emulsions and suspensions. In the experiments, droplets moved in the high-temperature (800–1200 K) gaseous medium consisting of hot air and the flow of combustion products. The authors (Strizhak et al., 2016; Volkov et al., 2016) used high-speed recording cross-correlation software and hardware systems, as well as panoramic techniques, such as particle image velocimetry (PIV), interferometric particle imaging (IPI), particle tracking velocimetry (PTV), and shadow photography (SP). They proved experimentally, using the example of single droplets and an aerosol flow, that the evaporation rates differ greatly for each droplet in the flow. The main reason why this happens is that temperatures also differ significantly near each droplet when it evaporates while surrounded by others. Based on the experimental results (Volkov et al., 2016), the authors formulated the hypothesis explaining the reasons for the coagulation of the droplets following each other in a high-temperature gas. Furthermore, they developed models (Kuznetsov et al., 2015) describing some important physical processes. In particular, the models indicate that the temperature and concentration of water vapor in front of the first droplet is substantially different from those in front of the second droplet. A similar effect was observed between any other two droplets immediately following one another. The analysis of experimental results (Strizhak et al., 2016; Volkov et al., 2016) and mathematical simulation (Kuznetsov et al., 2015) gives ground to assume that the temperature plummets in the trace of the droplets moving in front. Moreover, the authors explained the main reasons for this temperature reduction: (i) heat transfer from hot gas to a relatively cold water droplet, and (ii) endothermic phase transitions that lead to a substantial consumption of gas energy for evaporation. However, the hypothesis based on mathematical simulation (Kuznetsov et al., 2015) has not yet been proved experimentally.

It is next to impossible to verify the hypothesis (Kuznetsov et al., 2015) only relying on the results of the experiments performed in real flames and combustion products (Strizhak et al., 2016; Volkov et al., 2016), because turbulent pulsations typical of such flames make it difficult to monitor the temperature in certain parts of the droplet trace. In the case of a water aerosol, the difficulty to control the temperature is usually due to continuous collisions, coagulations, and fragmentations of droplets. Therefore, it is a relevant task to register the temperature in the trace of a stationary single droplet (and a small group of droplets) in the gas flow. Furthermore, we propose to vary the following major parameters to prove the mechanism of temperature reduction in the droplet trace: the droplet size, number and arrangement of droplets as well as the temperature and velocity of gas flow. In addition, we are going to perform experiments with solid bodies of the shapes and dimensions similar to those of water droplets.

The objective of this work is to determine experimentally the features of temperature reduction in the trace of the water droplets streamlined by the hot air flow and to outline significant heat and mass transfer processes and phase transitions.

2. Experimental setup and procedure

2.1. Experimental setup

Fig. 1 shows a scheme of the experimental setup developed for this study. A cylinder *4* (of 0.3 m high, 0.15 m in diameter) served as a chamber with a high-temperature gas flow. The cylinder was made of quartz glass. A technological hole (0.015 m in diameter) was drilled in a side wall at a height of 0.15 m. A supercharger *1* and a heater *2* generated an air flow with a temperature of T_g^0 inside the chamber. We selected the medium range of T_g^0 (from 473 K to 773 K), because it is typical of applications such as those listed in references (Sazhin et al., 2011; Avdeev et al., 2012; Varaksin, 2013; Hernández-Bocanegra et al., 2013; Strizhak et al., 2016). T_g° was monitored by a low-inertia type K needle thermocouple *6* (with a temperature measurement range 223–1473 K, systematic error ± 3 K, and inertia no more than 0.5 s) and a National Instruments 9213 registration complex.

We used a Finnpipette Novus dispenser (volume range from 1 μl to 10 μl, with 0.1-μl increments) to generate water droplets of the desired size. The initial volume of water droplets (V_d) ranged between 10 and 20 μl and the initial droplet radius (R_d), from 1.3 mm to 1.7 mm. A droplet with a known initial radius R_d was placed on the nichrome wire (0.1 mm in diameter) fixed on a minirobotic arm *3* (see Fig. 1). The minirobotic arm inserted water droplets into the cylinder through the side hole with hot air. A low-inertia thermocouple *6* was placed on the minirobotic arm. The thermocouple registered the air temperature before inserting water droplets, as well as the temperature in their trace, i.e., behind the droplets at a given distance *l*. This distance varied from 2 mm to 8 mm. The rate of inserting the droplets from the side wall to the axis of symmetry of the cylinder *4* did not exceed 0.5 m/s. This limitation stems from the need to prevent the detachment of droplets from the holder (nichrome wire).

2.2. Gas velocity

The initial airflow velocity (U_g^0) varied from 1 m/s to 5 m/s. When $U_g^0 > 5$ m/s, droplets detached from the holder. The initial velocity (U_g^0) and gas velocity behind a droplet (U_g) were monitored using a cross-correlation hardware and software package as well as PIV (Rau et al., 2016; Ayati et al., 2014; Birvalski et al., 2014).

Titanium dioxide tracer particles were injected into the incoming flow. Their tracks indicated two-component velocity fields and the values of U_g. The size of these particles was 10–50 nm and their concentration was low (0.5% volume fraction). The Stokes numbers for the tracers can be calculated using the expression $Sk = \rho_t d_t^2 U_g / \eta_g 2R_d$, where ρ_t is the tracer density (4235 kg/m^3); d_t is the maximum diameter of a tracer (50 nm); η_g is the dynamic air viscosity (2.6×10^{-5} to 3.6×10^{-5} kg/(s m)). For the conditions of the experiments, the velocities U_g varied from 1 m/s to 5 m/s and the radius of water droplets, from 1.3 mm to 1.7 mm. The Stokes numbers were within the range 0.08–0.59. The concentration of tracers 35–50 nm in diameter did not exceed 30%. The size of other particles varied between 10 and 35 nm with Stokes numbers not exceeding 0.21. Since $Sk < 1$, we can conclude that the particles of titanium went round water droplets with the gas flow.

The area where a water droplet (or a clay particle of the same initial size) was placed, was cut by a pulse laser light sheet (recurrence rate 15 Hz, energy per pulse no more than 70 mJ, wavelength 532 nm, max pulse duration 12 ns). The strip cut out by the light sheet was recorded by a cross−correlation video camera (2048 × 2048 resolution). Pairs of images were registered with a frequency of 15 Hz (the delay between the frames within one pair was 100 ms). Each experiment included at least 500 frames. The videograms were then processed using a cross-correlation algorithm. The video frames were split into elementary regions 32 × 32 pixels each and a correlation function was calculated for each of them. In order to reduce the number of random correlations due to pair loss, we used a top hat filter. This reduced the impact of tracers located in close (up to 1 pixel) vicinity to the outer borders of the computational region of a video frame. After that, we determined the tracer velocities using the known time delays between laser flashes and the most probable particle movements (determined by the maximum of the correlation function) in the registration regions of the video frames. Special software was used for all the calculations. The obtained velocity fields were av-