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Temperature traces of water aerosols, water-based emulsions, solutions and slurries moving in a reversed flow of high-temperature gases

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ABSTRACT

Over the recent years, a number of studies have been dedicated to heat and mass transfer during the interflow of gases and aerosols. The most important task here is to control the temperature of the forming gas-vapor mixture. The temperature of the latter is difficult to maintain for a long time on a level, required for the application in thermal and flame liquid-cleaning systems, fire extinguishing, or production of power-efficient heat carriers based on flue gases, water vapor, and droplets. Temperature prediction is difficult due to nonlinear dependence of phase transformation rate, which is dominant in extensively heated gas-steam-droplet systems, versus temperature. This work provides experimental study of temperature variation range in typical sections of combustion product flow during aerosol injection. To extend the practical value of the studies for the aforementioned applications – fire extinguishing in the first place – the experiments were conducted with water aerosols as well as water-based solutions, suspensions, and slurries. Initial temperature of combustion product flow was varied in the range of 400–1000 K. Aerosol properties: droplet size 0.01–0.35 mm, droplet volume density $(3.8\text{–}10.3)\cdot 10^{-5}\,m^3$ of droplets/m^3 of gas, initial injection velocity 1–3 m/s, concentration of additives (foam agent, slurry particles, etc.) 0.5–5%. We have established the lifetimes of the aerosol temperature trace. They may differ severalfold depending on the liquid composition used, for instance, water, solutions, slurries, and emulsions. In particular, dependences are presented showing a significant temperature variation in the trace of a droplet aerosol when a small amount (under 1%) of solid or liquid dopants is added. We have derived the approximating equations for all the dependences determined. We have also analyzed several causes of decreases in the temperature of gas-vapor mixture due to heat and mass transfer as well as the predominating phase transformations. Furthermore, we have established the effect of different commonly used additives on forming the sustained temperature trace of water aerosol flow. The experimental distributions of temperatures in the droplet trace and their recovery time serve as a basis for models of heat and mass transfer and phase transformations induced by droplet flows passing through high-temperature gases.

1. Introduction

Gas-steam-droplet flux is a fundamental element for a number of technologies used in chemical and petrochemical industry [1,2], as well as power industry [3,4]. One of the main applications of droplet flux, in which it is virtually the only option, is fire extinguishing [5–7]. However, parameters of any technology are chosen empirically most of the time, based on the results of experiments conducted with a certain degree of approximation to a real-life process. In this respect, droplet flow is usually considered a medium of monodisperse or polydisperse droplet formation with volume-averaged specifications (temperature, phase transformation rate, shape, velocity, etc.). In real life, when a droplet flow is moving, for example, in a high-temperature gas environment, every droplet affects the heating and evaporation of every following droplet, as was established by Volkov et al. [8]. However, the degree of this effect can be evaluated only by studying the temperature fields of the carrier gas mixture and evaporation in the droplet trace.

Most of the technologies that involve droplet flow movement through high-temperature environment (e.g., fire extinguishing) imply using water-based emulsions, solutions or slurries instead of pure water with no additives [9–12]. There are no experimental data on how temperature traces of water-based emulsion, solution and slurry aerosol are generated.

The main barrier to the development of the high-temperature gas-vapor-droplet technology is the lack of knowledge [1–5] on the complicated interconnected heat exchange processes and endothermic

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Nomenclature

R_d	droplet radius, mm
ΔR_d	parameter of droplet size variation due to evaporation, relative to its initial size, %
T_g	combustion product temperature, K
T_g'	gas-vapor mixture temperature in the trace of aerosol cloud, K
T_w	initial water temperature, K
ΔT_g	gas-vapor temperature variation in the droplet flow trace, relative to initial temperature of combustion products, K
t_{imp}	aerosol injection burst duration, s
U_d	droplet flow velocity, m/s
U_g	combustion product velocity, m/s
γ_b	foaming agent volume concentration, %
γ_c	clay mass concentration, %
γ_d	droplet volume concentration in the sprayed flow, m^3 of droplet/m^3 gas
γ_s	salt mass concentration, %
δ_T	deviation (in percentage of maximum) of ΔT_g for water without additives from ΔT_g for emulsions, slurries, and solutions under study, %
δ_τ	deviation (in percentage of maximum) of τ for water without additives from τ for emulsions, slurries, and solutions under study, %
τ	lifetime of lowered temperature of combustion products in the trace of droplet flow, s

phase transformations occurring when water droplets and vapors move in high-temperature gas flows. An important condition of the effective work of the gas-vapor-droplet technology is the homogeneous heating and evaporation of water droplets in a gas flow as well as the forming gas-vapor mixture. Experimental results obtained from fast-response contact and non-contact recording tools and mathematical modeling (in particular, [13–15]) illustrate a significant difference between the characteristics of droplet heating and evaporation in the front and in the trace of the aerosol. Therefore, we formulated a hypothesis that a gas-vapor mixture formed in the droplet trace has much lower temperature than in front of the droplet [15]. By comparing the experimental data and mathematical modeling, Voytkov et al. [15] ascertained that the typical dimensions of the temperature trace of a single water droplet are (5–7)R_d, that is, several of its typical sizes. This range makes it possible to forecast the necessary conditions of the droplet aerosol injection (fineness, time between pulses, and pulse length) to provide the maximum droplet evaporation in a high-temperature gas environment.

Volkov et al. [16] study experimentally how the incoming high-temperature gas flow affects droplet movement (entrainment, slowdown, turnaround). The dependences from [16] can be used to forecast the conditions facilitating the fullest possible evaporation of droplets moving in a gas environment and maximum decrease in the temperature of this environment. To minimize the entrainment of fire suppression liquid droplets by high-temperature combustion products, water is often replaced by slurries, solutions or emulsions. No experiments has yet been performed with the latter.

Before making such attempts, it is sensible to experimentally study the temperature in the trace of the corresponding droplet aerosols in comparison with water without additives as well as ascertain the maximum differences between the lifetimes of temperature traces, i.e., areas with lower gas-vapor environment temperature relative to the initial one. Kuznetsov et al. [13,14] measured such temperature of the gas-vapor mixture in the trace of a single droplet and a small droplet group of 2–5 droplets with different relative disposition. In order to use the results of such measurements to develop real technologies, it is important to experiment with an aerosol instead of isolated droplets. Voytkov et al. [15] compared the temperature traces of isolated water droplets, aerosol, and a single water batch. They explained the main difficulties involved in reliable temperature recording in the trace of water batches and large water drops. Using the findings from [15], it is possible to evaluate how much the corresponding temperatures and lengths of their variation in the water droplet trace will differ depending on the mechanism of their supply to the high-temperature gas environment.

Unfortunately, adequate models simulating high-temperature evaporation of droplets of liquids, solutions, emulsions, and slurries have yet to be fully developed. For example, Vysokomornaya et al. [17] showed that the droplet heating and evaporation rates calculated using advanced models of heat and mass transfer and those obtained experimentally vary severalfold in the range of high temperatures over 600 K. Therefore, it is sensible to study the main parameters of temperature traces of evaporating droplets experimentally [13–15].

At the same time, to develop these studies [13–15], it is important to conduct experiments with droplet aerosols that have complicated component composition corresponding to the real applications (in particular, firefighting, thermal and flame water cleaning from impurities, direct contact heat exchangers, etc.) [4–12].

The purpose of this work is to determine experimentally the temperature drop and the lifetime of relatively low temperature zone in the trace of a discrete flow of emulsion, solution and slurry droplets.

2. Experimental setup and methods

The experiments performed as part of this research involved the recording of a set of parameters. Table 1 presents systematic errors of measuring the main parameters. In Sections 2.1–2.4, we describe the measurement methods and approaches in detail. When presenting the research findings in Section 3, we show confidence intervals in all the figures in the form of vertical lines on the corresponding curves.

2.1. Experimental setup

For our studies, we used the experimental setup schematically shown in Fig. 1. The main structure of the setup is the same as the one used in the studies by Kuznetsov et al. [13–15]. We used the slow-motion (frame rate up to $6\cdot 10^5$ fps, max capturing resolution 1280 × 1280 pix) cameras Phantom V411 and Phantom Miro M310, and a cross-correlation hardware-software platform based on the Quantel EverGreen 70 pulse laser. The setup (Fig. 1) enabled us to capture the behavior of gas-vapor-droplet mixtures with the help of different methods for optical diagnostics of multiphase environment: Particle Image Velocimetry (PIV), Stereo Particle Image Velocimetry (Stereo PIV), Particle Tracking Velocimetry (PTV), Interferometric Particle Imaging (IPI) and Shadow Photography (SP) [18–22].

Capturing and continuous monitoring (auto-tracking) of droplet flow was implemented by the Tema Automotive software [23,24]. All those procedures were essential to reliably determine the interface when calculating the lifetime of relatively cold temperature trace of droplet aerosol.

Table 1
Systematic errors of measuring the main parameters.

Parameter	U_d	U_g	R_d	T_g	T_w	τ	γ	γ_d
Unit of measurement	m/s	m/s	mm	K	K	s	%	m^3 of droplets/ m^3 of gas
Accuracy	0.015	0.015	$1.39\cdot 10^{-3}$	3	1.5	0.1	0.02	$0.05\cdot 10^{-5}$