Reducing the flue gases temperature by individual droplets, aerosol, and large water batches

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ABSTRACT

This study examines the traces of water droplets moving through high-temperature combustion products (initial temperatures are 430–950 K). The temperature of a gas-vapor mixture in the area of droplet traces is measured using low-inertia thermocouples (thermal lag is less than 0.1 s). The paper considers aerosol flows with droplet size of 0.04–0.4 mm and concentration of $3.8 \cdot 10^{-5}$–$10.3 \cdot 10^{-5}$ m^3 of droplets/m^3 of gas, as well as individual droplets (sized 1.5–2.5 mm), and relatively large water massifs (sized 22–30 mm). The typical gas temperature reduction in the trace of a moving liquid ranges from 15 K to 140 K. The times of keeping the low temperature of the gas-vapor mixture in the droplet trace are from 3 s to 30 s relative to the initial gas temperature. The study indicates how such factors as initial droplet size, velocities of the high-temperature gas flows, volume concentration of droplets, combustion products temperature and initial water temperature influence the integral characteristics of temperature traces of droplets. For the experiments with single drops, large masses and aerosol drops, the comparative analysis takes place for conditions, at which the convective heat transfer between liquid and combustion products dominates over an evaporation. The experimental data substantiate the hypothesis which suggests that the temperature traces of water droplets are kept during quite a long time even for small droplets. The experimental data are a key basis for the development of the drip systems of controlled gas temperature reduction via the intensification of phase transitions.

1. Introduction

Gas-vapor-droplet technologies are used in various industries [1–5], for example, in firefighting, thermal treatment of liquids, ignition of liquid fuels, processing the heated surfaces of power equipment, gas-vapor cleaning of different surfaces, defrosting of granular media, heat-transfer fluids based on flue gases, vapor, and water droplets, waste-heat recovery, as well as water heating in contact heaters at modern thermal power stations. However, it is quite difficult to talk about the broad and active use of high-temperature (over 1000 K) gas-vapor droplet technologies due to rather limited reliable experimental data.

M. Renksizbulut and M.C. Yuen conducted experimental and theoretical studies [6–8] examining the evaporation of water droplets in gases at a temperature of over 1000 K. The main research findings [6–8] are more accurate empirical equations of the type Nu = f(Re,Pr) describing heat transfer between liquid droplets and the gas environment. On the basis of such equations, physical and mathematical models were developed simulating the heating

and evaporation of liquid droplets in gases (for example, [9–14]). These models are usually based on the assumption that the entire energy supplied to the interface between the media is spent on the evaporation only. Such assumptions are incorporated in the computing algorithms of computational software (Ansys Fluent and others). In particular, some researchers [9] explain that the use of empirical equations of the Nu = f(Re,Pr) type make the calculations much easier. When comparing theoretical and experimental values of evaporation rates, satisfactory correlations (with a deviation of no more than 10%) can only be tracked at temperatures below 600 K. For instance, the authors of [14] performed such a comparison for the evaporation of individual water droplets in gases at a temperature ranging from 300 K to 1100 K. One of the possible reasons for this is the lack of an adequate description of endothermic phase transitions under the conditions when water vapor is formed around droplets. Vapor reduces the convective heat flux from gases to the liquid. In turn, the emission of water vapor increases the radiative heat flux [14]. Rapid liquid evaporation may lead to significant diffusion processes at the near-surface droplet layer. These processes are hard to describe using empirical equations of the Nu = f(Re,Pr) type. It is important to have experimental data on high-temperature evaporation of liquid droplets, the correspond-

Nomenclature

C_g	heat capacity of gas, J/(kg·K)		U_d	droplet velocity, m/s
M_d	mass droplet, kg		U_g	velocity of gases (combustion products), m/s
Q_e	water vaporization heat, J/kg		V_0	volume of water batch, l
R_d	initial droplet radius, mm		V_d	volume of droplet, m³
R_{d*}	droplet radius at the bottom of cylinder, mm		W_e	evaporation rate, kg/(m²·s);
ΔR	parameter characterizing the decrease in the radius of droplet (relative difference between the value of R_d at the top and bottom of cylinder),%		α	heat transfer coefficient, W/(m²·K)
			γ_d	initial volume concentration of droplets, (m³ of water)/(m³ of gas)
S	scale factor, mm/pix		Θ_*	ratio of the gas temperature in the trace of droplets to the initial one
S_*	ratio of S_e to S_w			
S_e	evaporation surface area, m²		λ_g	thermal conductivity coefficient of gas, W/(m·K)
S_w	area occupied by liquid, m²		ν_g	kinematic viscosity of gas, m²/s
T	temperature, K		ρ_g	gas density, kg/m³
T_g	temperature of gases (combustion products), K;		ρ_w	water density, kg/m³
T_g'	temperature of combustion products after injection of an aerosol, individual droplet, or water batch, K		σ_w	surface tension coefficient of water, N/m
			τ	time of the temperature recovery of combustion products in the trace of droplet to its initial value, s
ΔT_g	difference between initial and minimum temperatures of the combustion products in the trace of an aerosol, individual droplet, or water batch, K		τ_1	time point of water injection, s
			τ_2	time point of compete temperature recovery of combustion products in the trace of droplet to its initial value, s
t_m	time of passing (through the channel with combustion products) aerosol, drop or water batch from nozzle/dosing device/steel rod to first, second and third thermocouples, respectively, s		Nu	Nusselt number
			Pe	Peclet number
			Pr	Prandtl number
T_s	temperature of droplet surface, K		Re	Reynolds number
T_w	initial water temperature, K		We	Weber number
t	time, s			
t_{imp}	impulse (injection) duration, s			

ing thermocouple measurements as well as the analysis of how the motion of droplets in a gaseous medium affects the vapor layer forming around them.

The evaporation rates of the droplets moving in gases, as well as their surface temperature are quite difficult to determine, especially the temperature distribution over the cross section [14]. This can be explained by the fact that the liquid/gas interface moves and varies continuously due to the phase transitions and the droplet surface deformation under aerodynamic forces [14]. As a consequence, the empirical approaches are often used (e.g., [6–9]) to determine the main parameters of droplet evaporation. The ratio $Q_e W_e = \alpha(T_g - T_s)$ at the liquid/gas interface is considered to be classic. The heat transfer coefficient α is derived from the equations of the form Nu = 2 + 0.6Re$^{(1/2)}$Pr$^{(1/3)}$ [6–9]. Such assumptions can significantly simplify physical and mathematical models of the processes under study. This explains the widespread use of empirical approximations in many heat and mass transfer models, which describe the systems with evaporating liquid droplets. The evaporation rates obtained using these assumptions correspond to experimental data only within limited gas temperature ranges (usually, up to 600 K) [14].

Over the past few years, characteristic evaporation rates have been determined [15,16] for droplets of water, solutions, emulsions, and suspensions. Both individual droplets and groups of droplets were examined moving through combustion products and air at temperatures ranging from 600 K to 1200 K. These processes were observed through the use of panoramic optical flow visualization techniques, high-speed recording tools, and cross-correlation systems [15,16]. Studies [14–16] have demonstrated that evaporation rates have a strong nonlinear dependence on the gas temperature. Moreover, evaporation rates change during heating, because the droplet size decreases. This is most likely a major reason for the differences between simulation and experimental results [14–16]. Research [14] points out that the mathematical description of

evaporation requires the models that take into account the exponential dependencies of evaporation rates on the temperature. Moreover, study [14] indicates that evaporation rates may differ several-fold from those suggested in references [6–9] at gas temperatures of 1100 K. This situation illustrates the need to expand the current experimental database.

Certainly, one of the most important applications of research into water droplet evaporation in high-temperature gases is firefighting [17,18]. Experimental results [14–16] specified the optimal size, concentration, and initial temperature of droplets to intensify evaporation in the combustion zone. Moreover, recommendations were formulated for the fire-extinguishing systems operating with the combustion products of various flammable liquids and combustible forest materials. The fundamental ideas about the extinguishing processes suggest that such processes as the temperature reduction in the combustion zone and the displacement of combustion products and oxidizer by water vapor enable more effective firefighting. The second factor was examined in references [14–16]. The magnitude of temperature reduction in the combustion zone after the injection of liquid droplets remains almost unexplored experimentally.

Theoretical study [17] proposes a hypothesis that the gas temperature decreases significantly due to vaporization or heat transfer with a liquid combined with low temperature maintained for a long time (dozens of seconds). This hypothesis [17] was proved valid in experiments with the evaporation of one [19] and several [20] water droplets in high-temperature air. The droplets hung on specialized holders (rods) in the air flow. The authors measured the gas temperature at various distances behind the droplets to determine the temperature trace of an evaporating droplet. They also recorded the aerodynamic trace of an evaporating droplet [19,20] and monitored the changes in the speed of the gas due to its flowing around the droplet and water vapor blown from its surface to the gaseous medium. The experimental setups [19,20] do not