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TEMPERATURE OF GASES IN A TRACE OF WATER DROPLETS DURING THEIR MOTION IN A FLAME

by

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The paper experimentally investigates the integral characteristics of the processes involved in the reduction of gas temperature by injecting the aerosol flow of water droplets into a counter flow of combustion products (period of steady low gas temperature, T_g', compared to the initial, T_g, range of temperature decrease ($\Delta T_g = T_g - T_g'$), rate of temperature recovery, the geometric dimensions of the temperature traces and their lifetime). We use the following recording devices: fast-response thermocouples (heat inertia less than 0.1 second), a multi-channel recorder, a high speed video camera (up to 10^5 frames per second), as well as a cross-correlation hardware and software package (with optical methods for recording the front and trace of the aerosol). The temperature trace of an aerosol is defined as the area with the temperature T_g' lower than the initial T_g by at least 10 K. We determine how the following group of factors affects the characteristics of temperature traces of water droplets: size (0.04-0.4 mm) and concentrations ($3 \cdot 10^{-5}$-$11 \cdot 10^{-5}$ m^3 of droplet per m^3 of gas) of droplets in a pulse, the initial temperature of water (280-340 K), the duration of a pulse (1-5 seconds), the temperature (350-950 K) and velocities (0.5-5 m/s) of combustion products. The temperature in a trace of water droplets during their motion in a flame can be reduced due to rapid vaporization or heat exchange between the gases and water. The conditions are identified, under which the low temperature of gases in a trace of droplet aerosol can be preserved for a long time (20-30 seconds). Finally, we forecast the parameters of temperature traces under the conditions of actual fires with combustion product temperatures over 1000 K.

Key words: *water, droplets, aerosol, high-temperature gases, flame, combustion products, temperature trace*

Introduction

Among the main problems of modern fire extinguishing systems (particularly in a case of forest fires) are the following [1-3]: high consumption of extinguishing agent (for instance, water), small coverage of combustion sources, a too long time required for the fire suppression of in a forest area or in buildings and constructions, and high risk of general public and rescuers being exposed to fire and combustion products. These disadvantages often lead to the necessity [1-3] of too many aviation departures for water withdrawal and its subsequent release into the combustion zone with a relatively low efficiency. As a result, fires (especially, those of forest crowns and brushes) can not be eliminated until it rains or until the bulk of the forest burns out.

Recent research aimed at improving the fire extinguishing technologies (for instance, [3-7]) show that extinguishing can become more effective given the rational use of water as

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well as water-based emulsions, solutions, and slurries. The authors suggest widely known methods of using water mist, water fog, and water curtains [3-7]. With the help of modern cross-correlation software, other works study how much the characteristics of fire suppression depend on size, concentration, and component composition of suspension droplets as well as the parameters of flame and combustion products [8-10]. An experimental information base has been accumulated [7-10] illustrating the possibility of effective fire suppression when embracing at least one of the two mechanisms: displacement of the oxidizer and the combustion products from the combustion zone; temperature reduction in the combustion zone. The authors prove [7-10] that the efficiency of fire extinguishing primarily depends on the temperature reduction pattern in the reaction zone. According to the results of numerical simulation [11-13], the maximum reduction of gas temperature in the combustion zone is possible by boosting the vaporization. Therefore, it is expedient to use water as a liquid with a high vaporization heat (2 MJ/kg).

Theoretical studies [11-13] illustrate that a monitored temperature reduction in the combustion zone can be achieved by selecting the size of the droplets and arranging them optimally in the flow. The authors highlight the so-called temperature and concentration traces of water droplets, *i. e.* the areas in a gas medium with lower temperature and concentration of combustion products (and higher water vapor concentration) emerging behind a droplet moving through the flames. They have also established [11-13] that the temperature in these traces can be predicted and controlled by choosing the optimal distances between droplets and their sizes. The research suggests a hypothesis [11-13] that under certain extreme conditions, the temperature in a droplet trace will only depend on only the evaporation processes or heat exchange between gases and water accompanied by an accumulation of gas energy. There have been no experimental justifications of this hypothesis so far.

The purpose of the present work is to study experimentally the dominant mechanisms of gas temperature reduction in a trace of droplet aerosol water flow during its motion in a high-temperature gas medium.

Experimental set-up and procedure

The scheme of our experimental set-up is presented in fig. 1. In terms of its basic elements, the set-up is similar to that used in research works [8, 9]. The experimental set-up, fig. 1, included four basic groups of equipment,
– assembly for temperature measurements (items 2, 3),
– equipment for monitoring and recording the parameters of droplet and high-temperature gas-flows (items 4-7),
– tools for creating an atomized droplet flow (items 8-10), and
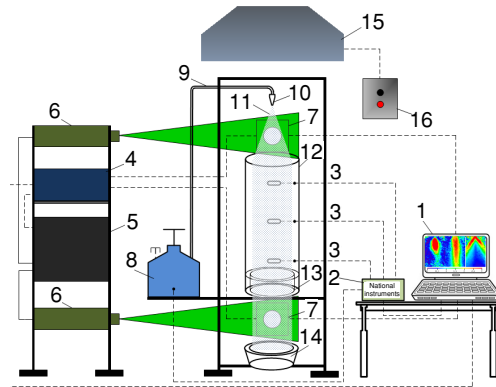– tools for creating a high-temperature gas-flow (items 12-16).

To record the initial temperature of gases, T_g, and the temperature of vapor-gas medium, T_g', in a trace of a droplet flow, we applied the measuring system consisting of high-speed analog input card (National Instruments) (2) and three quick-response (thermal lag less than 0.1 second) type K thermocouples (3) (temperature range 223-1473 K, systematic error ±3 K). The initial water temperature T_w was varied within the range of 280-340 K and monitored with a type L thermocouple (temperature range 273-473 K, systematic error ±1.5 K, thermal lag up to 10 second) in container (8). Water temperature (over 300 K) was increased using a set of heating elements (heaters) inbuilt in container (8). To ensure the temperature of about 280 K, we performed thermal insulation of container (8) using ice. Maximum random errors of temperature measurement were 8 K for T_g and T_g', and 3 K for T_w.

To create a flow of high-temperature combustion products, we used cylinder (12) (1 m high, 0.2 m in internal diameter) made of heat-resistant quartz glass and hollow cylinder (burner) – 13 (0.1 m high, 0.15 m in inner diameter and 0.19 m in outer diameter). The latter was filled with kerosene (TS-1), a fuel with well-studied and stable characteristics. It was ignited before the experiments. Temperatures of combustion products inside the cylindrical channel varied within the range of 350-950 K – temperature T_g decreased in the direction from burner (13) to the upper edge of cylinder (12).
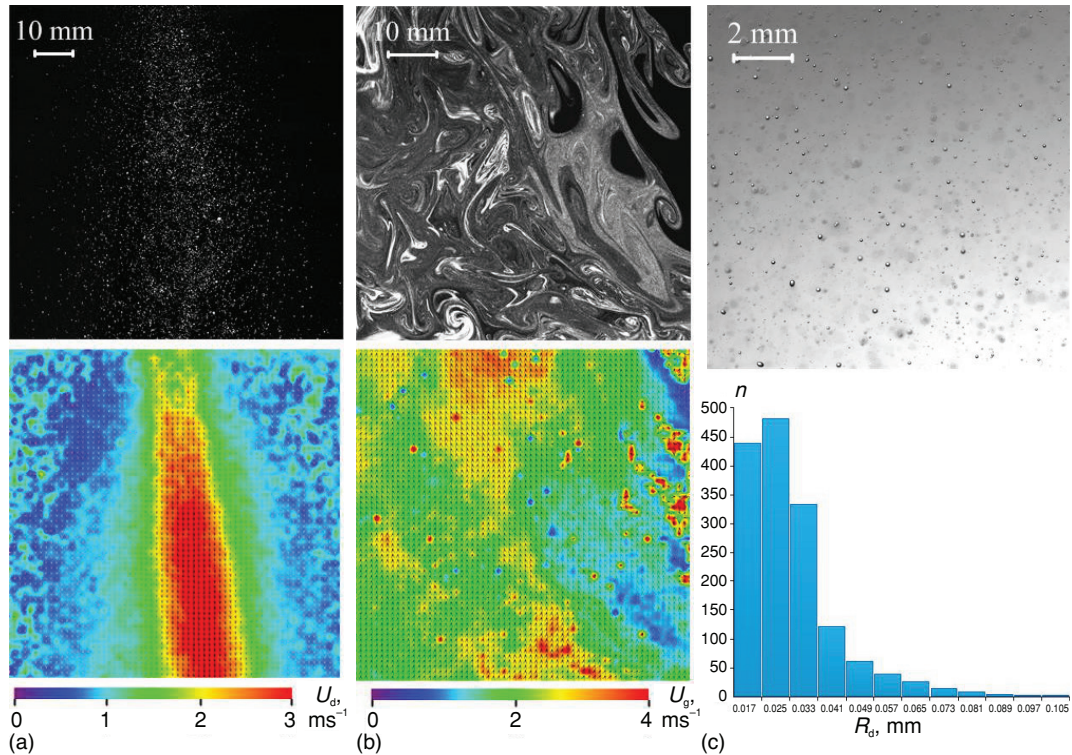
To generate a droplet flow of atomized water, we used a system consisting of container with water (8) (liquid was under pressure of 100-300 kPa), channel of water supply (9) and atomizing nozzles (10). Three types of atomizing nozzles were used to generate various (in dispersability) droplet flows: coarse atomization R_d = 0.08-0.4 mm, medium atomization R_d = 0.06-0.18 mm, fine atomization (water fog) R_d = 0.04-0.12 mm. The selected ranges of droplet size variation corresponded to

Figure 1. Scheme of experimental setup;
1 – personal computer (PC), 2 – high-speed analog input card, 3 – thermocouples, 4 – synchronizer of signal, 5 – power unit of laser (radiation generator), 6 – double pulse Nd:YAG laser, 7 – cross-correlation CCD video camera, 8 – container with water, 9 – channel of water supply, 10 – atomizing nozzle, 11 – droplet flow, 12 – quartz glass cylinder, 13 – burner, 14 – droplet catcher, 15 – plenum syste, 16 – on/off panel of the plenum system

those used in fire extinguishing by atomized water. Volume concentration of droplets in an atomized flow, γ_d, ranged from $3 \cdot 10^{-5}$ to $11 \cdot 10^{-5}$ m^3 of droplets per m^3 of gas. For these purposes, we used several (up to three) atomizing nozzles simultaneously providing the equal range of droplet size in the experiments.

As a technical means of determining the velocities of combustion products, U_g, droplets, U_d, and their radii, R_d, we applied a diagnostic system measuring the parameters of multiphase media and based on the following panoramic optical methods: particle image velocimetry (PIV), particle tracking velocimetry (PTV), interferometric particle imaging, shadow photography, and others [14-17]. The values of the U_g, U_d, and R_d parameters were kept identical (admissible deviations did not exceed the random measurement errors of U_g, U_d, and R_d) in each experimental series.

We recorded the initial velocities of the droplet flow by the PIV system [14, 15]. The droplet flow was cut by Nd:YAG laser ray (6) with a frequency of 15 Hz in a vertical plane. The laser was equipped with a set of cylindrical lenses to adjust the expansion angle of its line within the range of 5-45° (the angle was chosen according to the size of the area to be measured). Cross-correlation CCD video camera (7) with the optical axis located orthogonally to the laser line plane recorded the video grams with droplet images caught in the laser line plane (synchronizing module (4) provided the automatic time referencing of laser flashes (6) and CCD video camera (7) frame capture). The obtained video grams of the droplet flow were kept on personal computer (1) where they were processed by a cross-correlation algorithm of velocity calculation [14, 15] (initial and final images of droplets were on different frames). We calculated the value of scale coefficient, S, and obtained two component averaged velocity fields of atomized water flow as a result fig. 2(a). In the areas of radical mixing of combustion products and aerosol droplets, we also applied the PTV and stereo PIV methods [14, 15], which are more advanced variations of the PIV method.

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Figure 2. Typical video grams of droplet and gasflows and result of their processing by optical methods; (a) PIV, (b) PIV, (c) SP

The PIV method was also used to monitor velocities, U_g. The velocities, of combustion products in cylindrical channel (12) were preset (0.5-5 m/s) by adjusting the capacity of plenum system (15). The velocities of combustion product flow were measured before each experiment with an injection of aerosol. We injected tracer particles of titanium dioxide nanopowder (particle size 0.5-2 μm) into the bottom part of cylinder (12). The particles were picked up by the flow of combustion products and continued their movement along the vertical symmetry axis of cylindrical channel (12). The CCD video camera (7) recorded the frames of combustion products in the top part of the experimental set-up. Then they were processed by the cross-correlation algorithm. Figure 2(b) presents a typical video gram of combustion product flow and the corresponding two component velocity field. Each experimental series of calculating the velocities U_d and U_g included no less than 500 video frames of the flow. With this approach, the error in determining the velocities U_d and U_g did not exceed 2% by using such approach.

The initial sizes (radii R_d) of water droplets in a gas-flow were determined by the SP method [16, 17] immediately before each experimental series. We installed a diffusing screen connected by optical fiber with Nd:YAG laser (6) behind droplet flow (11) in front of CCD video camera (7). Then we eliminated the noises and determined the borders of droplet images on personal computer (1) (by low and high-pass filtering of obtained images). The obtained images were binarized, which involved setting a threshold of intensity level (corresponding to the droplets within the focusing depth of the camera lens on the obtained image) and searching for the selected droplet images. This helped us obtain the co-ordinates of the droplet centers and their radii. We averaged them and plotted histograms with the distribution of the droplet

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size in the atomized flow. Figure 2(c) presents a typical image of droplet flow and a histogram of droplet size. The error of R_d calculated by the SP method corresponded to the value of scale coefficient, S, and did not exceed 3% in the conducted experiments.

Using the experimental results, (in the analysis of the histograms of the droplet size distribution in the flow obtained using the SP method) we calculated the parameter ΔR in a similar way to the work [18]. The parameter illustrates the scale of reduction in the size of droplets after their motion through the channel with the combustion products:

$$\Delta R = \frac{R_d - R_d^*}{R_d} \cdot 100\%$$

where R_d and R_d^* [mm] are droplet radii at the input and output of the channel with high temperature gases.

A series of at least ten experiments was conducted for each initial value of parameters γ_d, t_{imp}, T_w, R_d, U_d, and U_g. Each experiment involved of the following sequence of procedures.

- The inner cavity of cylinder (burner) (13) was pre-filled with kerosene in an amount of 250 ml, which was then ignited.
- Thermocouples (3) were installed at three points over the height of cylinder (12), fig. 1. We then started the continuous recording of the combustion product temperature in cylinder (12) with the use of thermocouples (3) and high-speed analog input card (2). The thermocouple readings were saved on personal computer (1).
- The pulsed supply of atomized flow into the inner cavity of cylinder (12) started after 250 second – the period necessary for the temperatures inside cylinder (12) to reach the necessary levels. The time delay between the pulses was varied in the range of 30-60 seconds, depending on the parameters of the experiment. The duration of one impulse, t_{imp}, ranged from 1-5 seconds.
- The data were saved on personal computer (1) for further processing. Figure 3 presents the typical temperature variation trends, T_g', in a trace of aerosol water flow during its pulsed supply.

From the experimental results, we defined the value of temperature reduction, ΔT_g, as well as the time, τ, when temperatures of combustion products in the trace of a droplet flow remained lower than the initial ones. The temperature trace of an aerosol was the area with the temperature T_g' lower than the initial T_g by at least 10 K. The parameter ΔT_g was calculated as the difference between the temperature of the combustion products at the moment of pulsed supply and their minimal temperature after the droplet aerosol passed through them. The parameter, τ, was the period between the point when the combustion product temperature began decreasing and the point when it returned to its original value (T_g'= T_g). The error in determining the values of τ did not exceed 1 second.
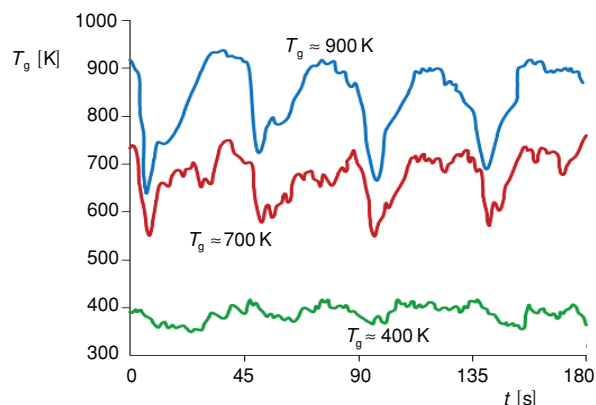
Figure 3. Typical temperature, T_g', variation trends in a trace of aerosol water flow during its pulsed supply for various initial values of temperatures T_g ($\gamma_d \approx 3.8 \cdot 10^{-5}$ m^3 of droplet per m^3 of gas, $T_w \approx 300$ K, $U_g \approx 0.8$ m/s, $t_{imp} \approx 1$ second)

Results and discussion

Figures 4-8 present the times, τ, when the temperatures of the vapor-gas mixture in a trace of water droplets remain low despite changes in their concentrations, γ_d, size, R_d, initial temperatures, T_w, and durations of pulsed supply, t_{imp}. In addition, we compared the values of τ for different gas temperatures T_g.

We have established that an increase in the size and concentration of droplets as well as gas temperature leads to a non-linear rise in the lifetimes of aerosol temperature traces. In all the figures, the times, τ, reach some steady-state values, which means that there are critical lifetimes of aerosol temperature traces. Most likely, they are caused not so much by processes of heat exchange between the gases and droplets as the aerodynamic features of the droplet movement in the channel (in particular, the limited length of the channel and a fairly significant heating of the walls). Nevertheless, these experiments helped us identify the dominant processes that determine the lifetimes of temperature traces. For instance, a good correlation with the previously highlighted features of evaporation processes was established by varying γ_d, R_d, T_w, and t_{imp} [18]. The experiments [18] have shown that if droplets are less than 100 μm in size, practically 80-90% of their initial amount evaporates at the inlet into a high temperature channel and they are taken away by combustion products. Thus, their influence on the lifetimes of temperature traces is very limited (minimal for the conducted experiments). Droplets ranging from 100 μm to 250 μm in size evaporated by 60-70% in the experiments [18] under the same conditions as in the present work. Significantly lower evaporation rates were established [18], when the sizes of droplets ranged from 250 μm to 400 μm and their size only decreased by 30-50% due to the evaporation. Since the surface area of the droplets so big was relatively large (in comparison with small droplets), the injection of vapors was enough for a significant decrease in T_g' in the conducted experiments, fig. 4.
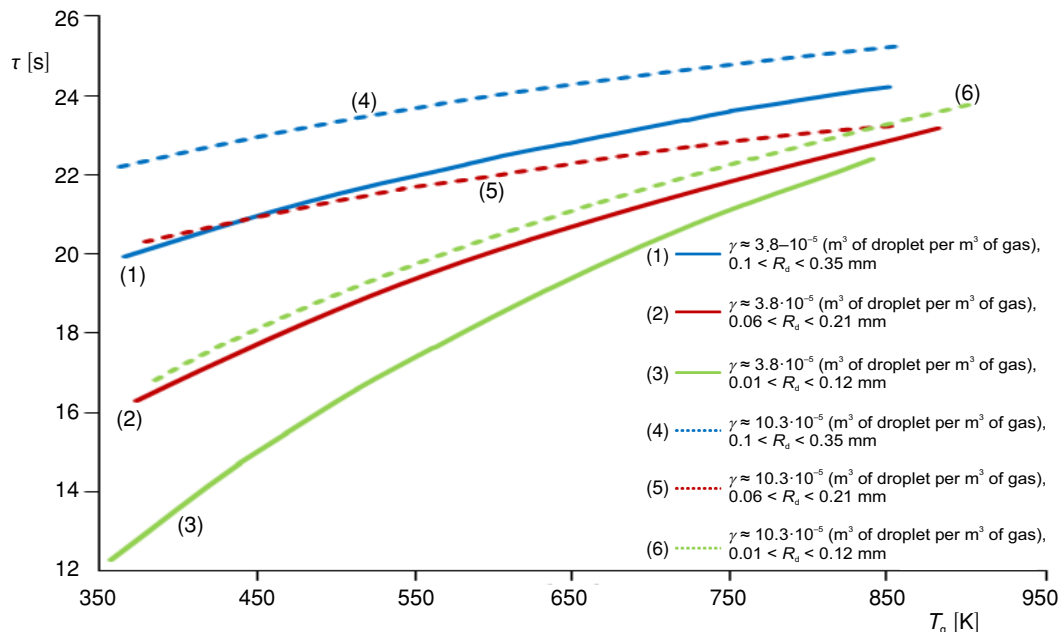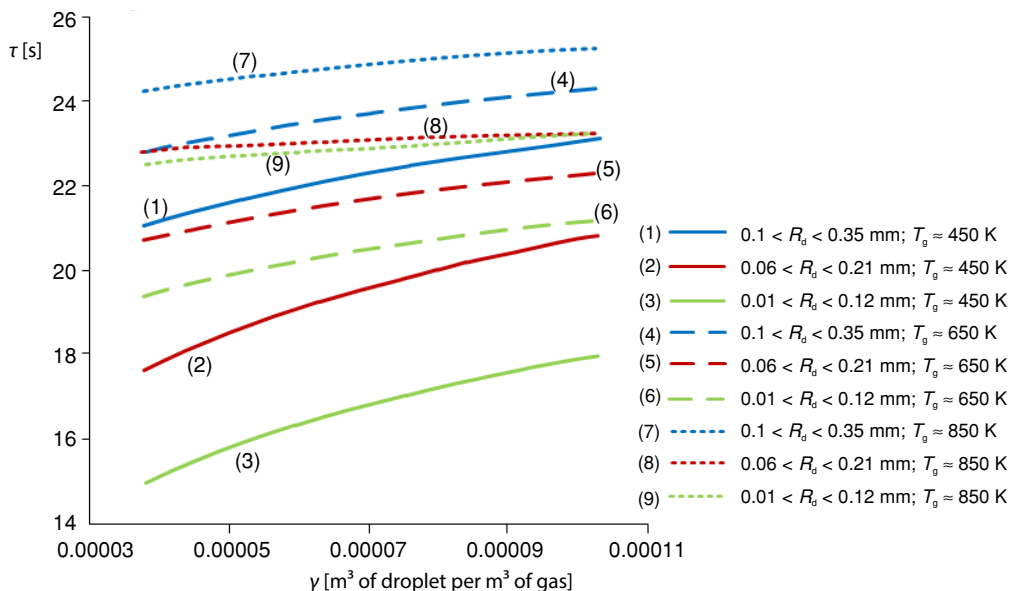

Figure 4. Times of lower temperature in a trace of droplet cloud *vs.* the temperature of gases (combustion products) with various droplet sizes and concentrations in an aerosol ($T_w \approx 300$ K, $U_g \approx 0.8$ m/s, $t_{imp} \approx 1$ second)

A comparison of the results of varying the droplet concentration, γ_d, with the data from [18], we have established quite a good correlation. In particular, we have discovered [18] that, for instance, for droplets with $R_d \approx 0.12$ mm, the values of the parameter ΔR illustrating the rate of R_d change during evaporation go down from 70% to 57% if the concentration increases from $3.8 \cdot 10^5$ m³ of droplet per m³ of gas to $10.3 \cdot 10^5$ m³ of droplet per m³ of gas. The scale of ΔR variation *vs.* concentration γ_d becomes more moderate with an increase in the droplet size and temperature of the gases. Similar conclusions can be made from the analysis of figs. 5 and 6. The shape of the curves is in good agreement with the experimental results of studying the characteristics of the droplet evaporation [18]. Figures 5 and 6 allow concluding that a more rapid evaporation induces a steeper drop in temperature during the droplet motion and a longer lifetime of the temperature trace. However, the results presented in fig. 7 show that this conclusion needs some clarification.
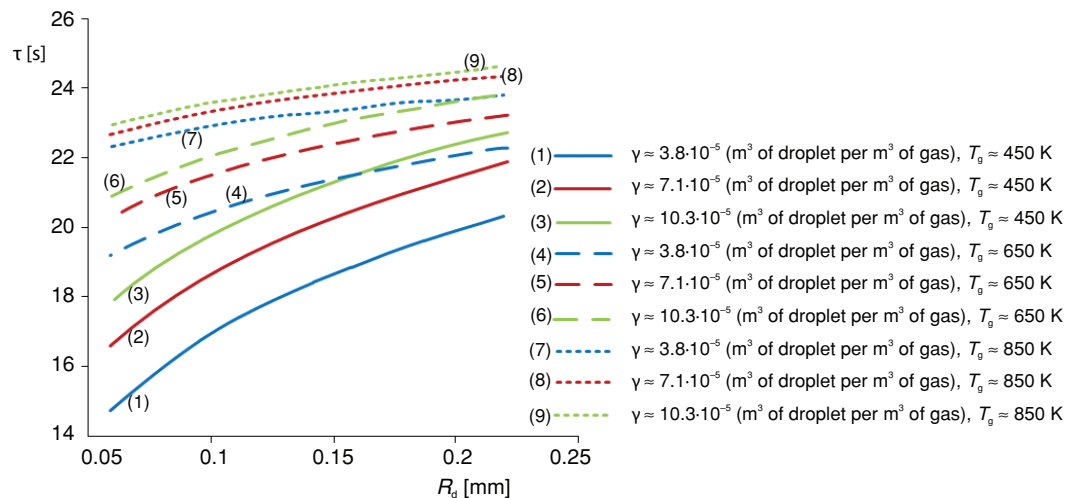

Figure 5. Times of a steady lower temperature in the trace of a droplet cloud *vs.* volume concentration of droplets in a flow with various sizes of droplets in an aerosol and temperatures of combustion products ($T_w \approx 300$ K, $U_g \approx 0.8$ m/s, $t_{imp} \approx 1$ second)

Figure 7 shows the characteristic values of the lifetimes of water droplet temperature traces at various initial temperatures. The times, τ, become shorter with the rising temperature T_w. The experiments [3] illustrate that the pre-heating of water leads to a significant acceleration of droplet evaporation, since the warm-up time of the droplet is minimized. In particular, they show [3] that the evaporation rates of water droplets ranging in size from 100 μm to 250 μm with a change in their initial temperature from 290 K to 360 K are increased by 30-40%. The variation of evaporation rates for bigger droplets becomes more moderate. Therefore, pre-heating for small droplets can significantly influence the temperature in a droplet trace.

The growth of initial water temperature does not increase the lifetime of a temperature trace (as might be expected in accordance with the results of [3]) but reduces it, fig. 7. This occurs because the droplet size decrease faster with the growing T_w in high temperature gases during evaporation like in experiments [3], but the heat content of the aerosol itself is high because of an increase in the initial temperatures T_w. As a consequence, the gas-vapor medium

forms faster in a trace of the aerosol flow and its temperature corresponds to the maximum temperature of water boiling. Since the gas-vapor medium is characterized by a lower thermal conductivity than water, the further warming of droplets reaches a steady-state. The proportion of energy consumed for vaporization becomes almost constant, and the energy brought by the heated aerosol increases with the growth of temperature T_w. As a result, we obtain a decrease rather than an increase in the temperature in a droplet trace, if water is pre-heated.

Figure 6. Times of a steady lower temperature in the trace of a droplet cloud *vs.* the size of droplets in an aerosol flow at various temperatures of combustion products and droplet concentrations in an aerosol ($T_w \approx 300$ K, $U_g \approx 0.8$ m/s, $t_{imp} \approx 1$ second)
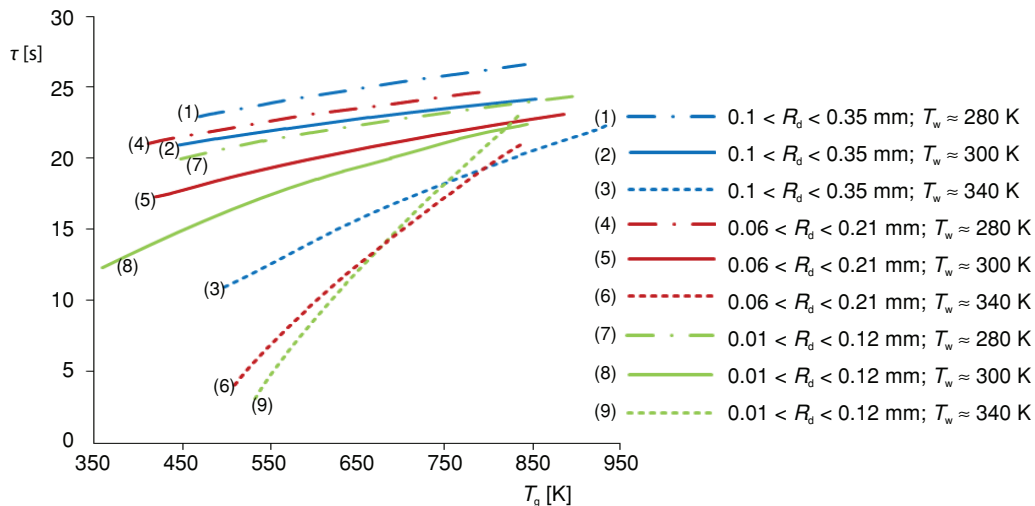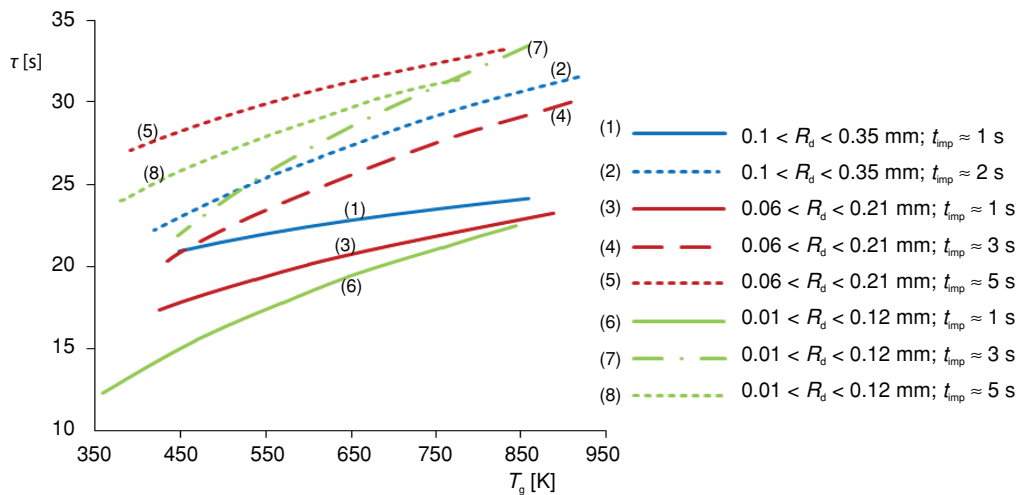

Figure 7. Times of a steady lower temperature in the trace a of droplet cloud *vs.* the temperature of gases (combustion products) at different initial temperatures and sizes of water droplets ($\gamma_d \approx 3.8 \cdot 10^{-5}$ m^3 of droplet/m^3 of gas, $U_g \approx 0.8$ m/s, $t_{imp} \approx 1$ second)

Figure 8 shows that the greater the duration of the aerosol supply (injection) into the area filled with the combustion products, the longer the lifetime of the temperature trace, τ. We

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obtain this result, because the injected volume of water rises almost linearly with an increase in the pulse duration and, therefore, the volume of water vapors grows non-linearly. Moreover, droplets of the aerosol move as a flow (as quite a big group of lines of a sort). Experiments [19] show that each subsequent droplet, while moving in the trace of the previous droplets, is surrounded by a gas-vapor medium with a much lower temperature (relative to the previous droplets). As a consequence, the evaporation rates of the subsequent droplets are lower than those of the first ones. But the temperature of gases decreases even more with each new line or portion of droplets. The main reason for this is an increase in the concentration of water vapors and rapid heat exchange of gas mixture with a relatively cool new portion of the injected aerosol.

Figure 8. Times of lower temperature in the trace of a droplet cloud *vs.* the initial temperature of gases (combustion products) at different pulse times and sizes of droplets in an aerosol ($\gamma_d \approx 3.8 \cdot 10^{-5}$ m^3 of droplet per m^3 of gas, $U_g \approx 0.8$ m/s, $T_w \approx 300$ K)

The estimated heat flows in the *aerosol – high-temperature gas* system show the domination of the radiant heat exchange of liquid droplets and gas medium [20]. Convective thermal fluxes are several times lower than the radiant one when the temperature of gases exceeds 850 K. Conductive heat exchange with relatively cold droplets of water is less intensive – values of the corresponding thermal flux are almost an order of magnitude lower than those of the radiant and convective ones. The vapors forced in from the droplet surface intensify the radiant heat exchange and reduce the conductive one [20]. The latter becomes less intense as vapors have substantially lower thermal conductivity and thermal diffusivity as compared to water. The radiant heat exchange increases, since water vapors are characterized by the highest values of emissivity coefficients of the gas mediums. As a result, the heat sink to the vaporization borders from the gas medium is intensified. These conclusions [20] suggest that the vaporization process is the determining one, when setting the temperature in the trace of the aerosol flow (especially for high-temperature gas-vapor-droplet applications).

The conducted experiments show that an increase in gas velocity, U_g, leads to a non-linear reduction in the lifetime of the temperature traces. In particular, the values of τ went down from 20-30 second to 7-12 seconds, when U_g went up from 0.5 m/s to 5 m/s. This result is due mainly to a significant reduction in the lifetime of droplets in the gas channel and, thus, accelerated vaporization. Droplets and forming water vapors are carried by gas-flow away from the installation points of thermocouples in the channel.

The obtained results allow us to predict that under the conditions of real fires (temperature of combustion products over 1000 K), the temperature of gases can be significantly reduced (by several hundred degrees) if the pulsed supply of the aerosol (during 1-5 seconds) is introduced. At the same time, the period of temperature recovery in the flame fire zone is mainly determined by the velocity of the combustion products. In the case of high velocities, U_g, it is expedient to increase the droplet size in order to prevent the droplets from being carried away from combustion products and to minimize the growth of τ. In the case of relatively low U_g, a significant reduction in the gas temperature and longer times τ can be achieved even with a small droplet size (up to 0.2-0.3 mm).

The aspects that we have established do not only expand the fundamental concepts behind the heat exchange of aerosols with high-temperature gas mediums, but also have applied relevance in fire-fighting. In particular, research findings (for instance, [21, 22]), show that effective fire suppression requires a temperature reduction in a combustion zone as fast as possible (it is particularly important to reduce the temperature directly in the flame zone). The obtained experimental dependences show that the formulated problem can be solved with a short-period (pulse) supply of droplets (hence minimum water expenditure). The choice of a particular size of droplets, their concentration, temperature and pulse duration will be determined by gas temperature, its velocities and the height of the flame combustion zone. The conducted experiments and data [20] show that it is expedient to search for the balance between the water droplets that are carried away and those continuing to move for the rational use of water for fire-fighting. Smaller water droplets can accelerate the evaporation, but the vapor and droplets can be carried away by combustion products. Using large droplets involves higher water expenditure. The established dependences illustrate the possibility to determine the average size of droplets that would meet the requirements of both the minimum consumption and maximum temperature reduction in the combustion zone.

Technologies of thermal (in particular, fire) purification of liquids can serve as another possible application of these research findings. The presented experimental information can be used to optimize the corresponding purification units by regulating the lifetimes of relatively low gas temperature and rates of its return to the initial values, as well as lifetimes of droplets, when these are supplied from atomizers by stages. The proposed experimental approach can optimize the operation of purification chambers, if γ_d, R_d, T_w, T_g, t_{imp} and other investigated parameters are controlled.

Conclusions

Due to the conducted experiments, we were the first to prove the hypothesis [11-13] that it was possible creating stable temperature traces by pulsed injection of an aerosol flow of water droplets into high-temperature combustion products and maintaining the low temperature of gases for quite a long time (up to 20-30 seconds).

The analysis of how a group of factors affects the times when the gas temperature in a trace of water droplets remains lower (relatively to the initial one) allowed us to establish the dominant role of two mechanisms (evaporation and heat exchange between water and combustion products). We determined the conditions, under which each of the highlighted mechanisms predominates significantly over the others.

It is expedient to develop the suggested approach to assessing the effectiveness of using water droplet flows under near-real conditions to improve other high temperature gas-vapor-droplet technologies. Such technologies may include heat carriers based on furnace gases,

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vapors and droplets of water as well as specialized droplet flows for processing thermally loaded surfaces of power equipment and defrosting of granular medium.

Acknowledgment

Nomenclature

R_d – initial droplet radius, [mm]
R_d^* – droplet radius at the output of high-temperature gases, [mm]
ΔR – parameter characterizing the decrease in the droplet radius (relative difference between the value of R_d at the input and output of the high temperature gas medium), [%]
S – scale coefficient, [mm per pixel]
T_g – initial gas temperature, [K]
T_g' – temperature of vapor-gas mixture in a droplet trace, [K]
ΔT_g – difference between initial and minimum value of temperature of combustion products in a droplet trace ($\Delta T_g = T_g - T_g'$), [K]

T_w – initial water temperature, [K]
t_{imp} – duration of impulse (droplet injection), [s]
U_d – droplet velocity, [ms⁻¹]
U_g – gas velocity, [ms⁻¹]

Greek symbols

γ_d – initial volume concentration of droplets, [m³ of water per m³ of gas]
τ – recovery period of the temperature of combustion products in a trace of a droplet flow up to the initial value (from T_g' to T_g), [s]

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