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Evaporation Features of Water Droplets with Typical Subsoil Impurities During the Motion Through High-Temperature Gas Environment: Research Experience at Tomsk Polytechnic University

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Abstract

This paper investigates experimentally the evaporation rate of water droplets with typical subsoil impurities (clay, silt, soil, sand) during the motion through high-temperature gas environment. The experiments were conducted at Tomsk Polytechnic University using high-speed video recording and modern video processing methods. Here, we analyze the influence of the impurity concentration on the intensity of heating and phase changes. The present study defines, how the preheating of impurities affects the completeness of the evaporation of water droplets with impurities. As a result, of studies, we draw the conclusion that it is possible to use water from natural reservoirs without prior preparation for wildfires extinguishing.

Peer-review under responsibility of the Scientific Committee of LKTI 2015.

Keywords: Droplet; water; subsoil impurities; high-temperature gases; high-speed video recording.

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1. Introduction

Fire-fighting equipment and technologies are constantly developing due to increasing security requirements, traditionally large material losses during fires and ignitions, as well as the rapid progress of science and technology. Currently, there are dozens of ways to extinguish fires, which are used depending on the specificity of fire. Despite the variety of techniques for fire elimination, the most frequently used quenching substance is water. Among the most promising methods for extinguishing by water as quenching medium, there are technologies relating to water spray and the formation of emulsions based on it (Försth & Möller, 2013; Gupta, et al., 2012; Tang, et al., 2013; Vysokomornaya, et al., 2014; Xiao, et al., 2011; Zhou, et al., 2012; Yao & Cong, 2012). It should be noted that when water mist is used for extinguishing, flame elimination occurs mainly due to the decrease of the temperature and the concentration of components entering into a chemical reaction by phase transition. However, the access to water supply may be limited during large wildfire elimination. Therefore, water from natural reservoirs is used for extinguishing forest fires without pretreatment. At the same time, there is a high probability of the presence of impurities in water in the form of the particles of sand, silt, clay, soil, and etc. Under such conditions, it is possible to change the evaporation rate of sprayed liquid droplets; this may affect fire-fighting efficiency.

Among the scientists involved in the study of the designated problem, there is professor P. A. Strizhak, research engineer O. V. Vysokomornaya, graduate student A. O. Zhdanova and others, who work at the Department of Heat and Power Process Automation of the Institute of Power Engineering in National Research Tomsk Polytechnic University. The team works within the educational direction "Thermal Engineering and Heat Engineering" during the 2014/2015 academic year. Scientific results obtained during this period of time were applied in academic disciplines "Modern problems of power engineering, heat engineering and heat technologies", "Engineering Experiment".

The aim of this paper is to conduct experimental investigations to determine the effect of typical subsoil impurities (mud, clay, soil, sand) on the characteristics of water spray evaporation. Experiments were performed to develop the fundamentals of resource-efficient and safe technologies for extinguishing large forest fires distributed in time and space by polydisperse water droplet flows using aviation.

2. The experimental setup and methods

Our experimental setup (Fig. 1) included two high-speed video cameras *1* (the frame rate was up to $6{\cdot}10^5$ frames per second), a cross-correlation video camera *2*, a signal synchronizer *3*, and a specialized working station *4* (for data processing).

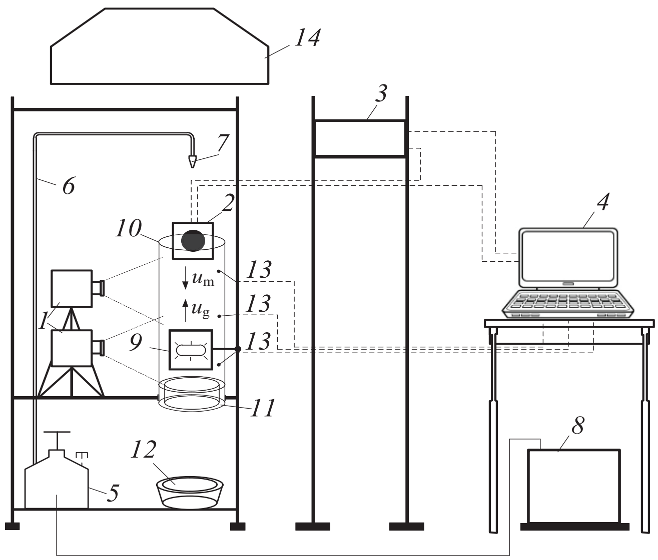

Fig. 1. Scheme of experimental setup: *1* – high-speed video camera; *2* – cross-correlation video camera; *3* – *s*ynchronizer for computer and cross-correlation cameras; *4* – personal computer; *5* – water tank; *6* – water supply channel; *7* – sprayer; *8* – chamber for heating and cooling water; *9* – spotlight; *10* – quartz tube; *11* – hollow cylinder with flammable liquid; *12* – water catcher; *13* – thermocouples; *14* – ventilation system.

The internal cavity of a cylinder *11* was filled with combustible liquid (acetone), which was then ignited. High-temperature gases (acetone combustion products) filled the entire inner cavity of cylindrical channel *10*. After about 200 seconds (time delay was necessary to achieve the required gas temperature in channel *10*), water with subsoil impurities was fed from a water tank *5* to the input of a dosing device *7* through channel *6*. The supply of droplets and their motion was carried along the symmetry axis of channel *10* from top to bottom. The initial sizes (d_0) and velocities (u_0) of water droplets ranged from 2 to 3 mm and from 2 to 4 m/s, respectively. When droplets were released from the dosing devise *7* with such velocities in the interval of 1 m, their velocities u increased up to 5 m/s. Video cameras *1* and cross-correlation cameras *2* (Fig. 1 shows only one camera; however, two cameras were used in our experiments) recorded droplets in free fall through high-temperature gas zone. Video processing was performed in the workstation *4* with the help of software "Tema Automotive", as well as other specialized algorithms.

We conducted at least 10 series of experiments under identical initial conditions (the initial droplet diameter d_0, initial droplet temperatures t_0, initial droplet velocities u_0, gas (combustion products) temperatures t_g, gas velocities U_g).

Gas temperature t_g (of combustion products) varied from 300 K to 1900 K in the experiments. Three type A-1 thermocouples *13* (temperature range 0÷2473 K, maximum permissible error ±0,005·$|T|$) were installed to monitor the temperature.

The initial temperature of water droplets with impurities was regulated in a range of T_w=280÷370 K. Water droplets with impurities were introduced into gas environment by the system of heating and cooling chambers. The temperature was monitored by a type L thermocouple (temperature range 233÷573 K, deviation Δ = 2.5 K).

Gas (combustion products) velocity U_g in cylindrical channel *10* was measured by a vane anemometer type "UnionTest AN110" (the maximum error – 0.1 m/s) and it was about 1.5 m/s. The ventilation system *14* enabled combustion product removal and air supply necessary for burning.

Images of water droplets with impurities were recorded at the input and output of channel *10*. In order to determine the droplet shape, the SP method was applied. SP method is based on the registration of the shadow picture of an object with a refractive index different from its environment. For this purpose, diffuse light source with uniform spatial intensity distribution was placed behind droplets in front of cross-correlation cameras *2*. Images captured by cameras *2* were digitally analyzed using software "Tema Automotive". Image analysis determined the position, shape and characteristic size R_d of droplets, as well as their velocity. Droplet sizes in considered videogram areas (before and after the flame zone) were determined from the video, which was a consistent set of videograms at a fixed time interval. Four liquid droplet maximum diameters (in pixels) were found. The average diameter was calculated as follows: $d_1=(d_{01}+d_{02}+d_{03}+d_{04})/4$. After that, the average diameter of the droplet was found by the formula: $d_{drop(pix)}=(d_1+d_2+..+d_n)/n$. The diameter in pixels was converted to millimeters at a certain (predetermined) scale factor S: $d_{drop(mm)}=d_{drop(pix)}\times S$ (mm/pixels); the corresponding average droplet radiuses were calculated. Then, the parameter was calculated that characterized the decrease of droplet during its motion through high-temperature gas area: $\Delta R=(R_d-R_d^*)/R_d$, where R_d, R_d^* – the conditional average radius of the droplet at the input and output of high-temperature gas zone, respectively, mm. Systematic errors in measuring the droplet diameter by high-speed cameras *1* at S=0.041÷0.055 mm/pixels did not exceed 0.05÷0.08 mm.

3. Results and discussion

Results of the experiments allowed revealing the dependencies of the characteristic size reduction of water droplets on the concentration of subsoil impurities (Fig. 2).

The analysis of dependencies presented in Fig. 2 allows drawing the conclusion that the presence of subsoil impurities intensifies significantly the evaporation of sprayed water droplets. This effect is especially explicit in the droplets of clay, silt and soil (Fig. 2, a, b, c). The evaporation rate increases by an average of 70 %, when the concentration of impurities in the droplet varies in a small range (from 0 to 1%).

This effect is probably due to the fact that these types of impurities absorb and accumulate flame radiation energy because of their thermal properties. This contributes to the accelerated heating and evaporating of droplets relative to the water without impurities.

The presence of sand in water droplets (Fig. 2, d) affect the droplet evaporation rate in the flame less significantly, since the emissivity of sand is lower than that of clay, silt and soil. However, sand impurity intensifies greatly phase transition, when the concentration of sand varies from 0 to 10 %.

It should be noted that the increase of the evaporation rate of quenching medium by introducing subsoil impurities into sprayed water droplets has no negative effect on the environment in a wildfire zone, unlike chemical methods.

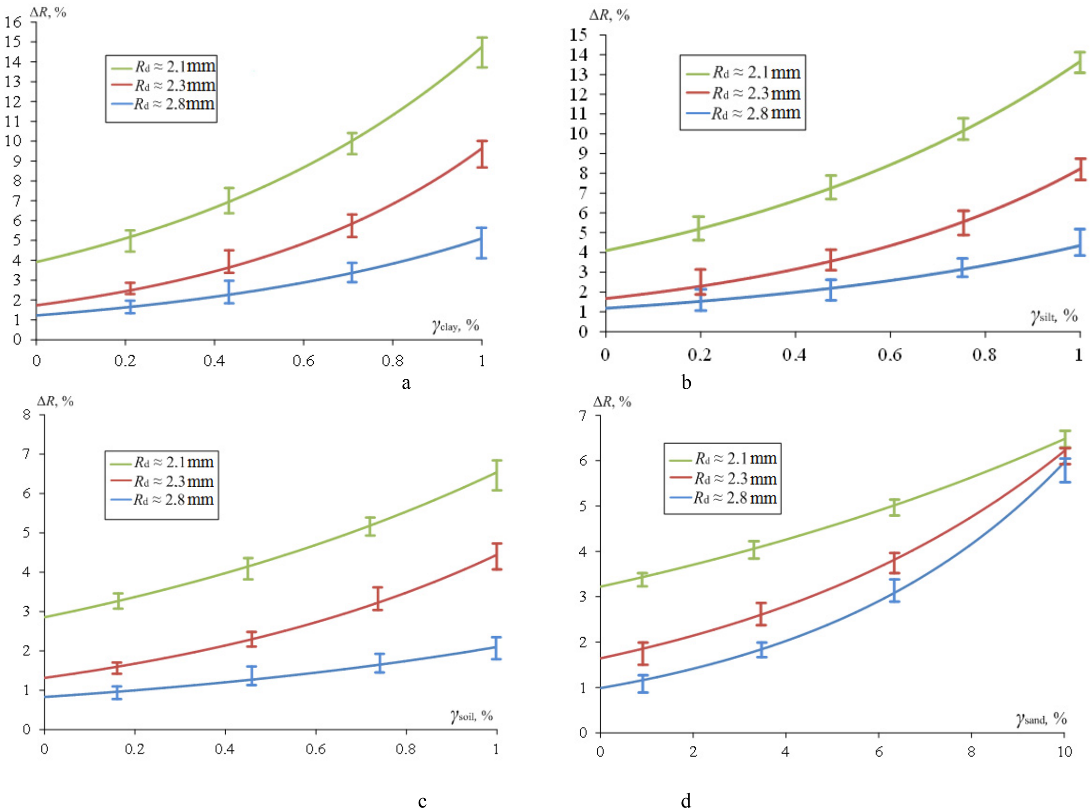

Fig. 2. Size reduction of water droplets ΔR depending on the concentration of subsoil impurities: (a) clay, (b) silt, (c) soil, (d) sand.

Also, we analyzed the influence of the initial temperature of water droplets with subsoil impurities on their evaporation rate. Fig. 3 shows the dependencies of the radius reduction of water droplets with impurities on the initial liquid temperature during the motion through the flame.

As might be expected, the increase of the initial temperature of sprayed water droplets with impurities increases their evaporation rate during the motion through high-temperature gas environment. However, the effect of the initial temperature on the rate of phase transition can be considered negligible for the practical application of the results, since the resulting positive effect does not allow compensating significant additional energy consumption for the preheating of extinguishing medium.

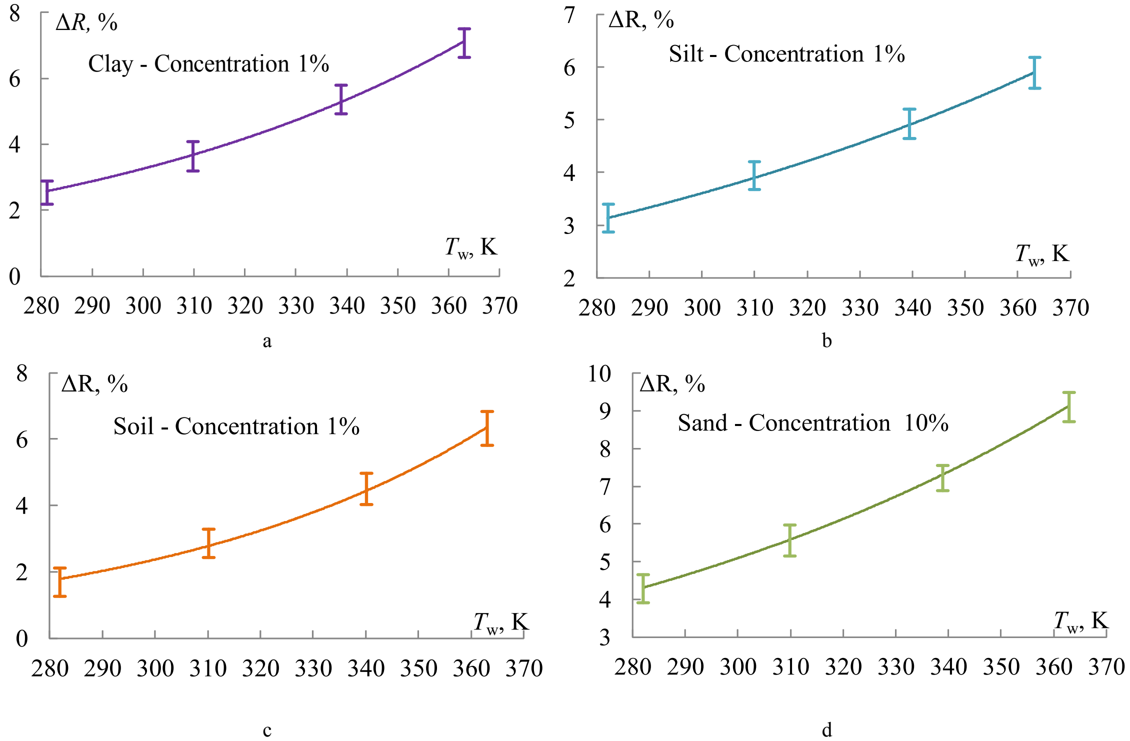

Fig. 3. Size reduction of water droplets ΔR with the initial radius R=2.8 mm depending on the initial temperature of droplets with the impurities of (a) clay, (b) silt, (c) soil, (d) sand.

However, it should be noted that the characteristic size of water droplets with subsoil impurities changes in average by 5÷10 % after passing the cylinder with high-temperature gases, when the initial droplet temperature varies from 280 K to 370 K. Thus, it can be concluded that water with the initial temperature as in natural reservoirs at the beginning of forest fire season, as well as water heated to near boiling temperature may be used with comparable evaporation efficiency.

4. Conclusion

The experimental studies have established the features of the evaporation of water droplets with typical subsoil impurities during the motion in the flame. It has been shown that the presence of subsoil impurities in spray water even at low concentrations can intensify phase transition during the interaction of water droplets with high-temperature gases. It has been also determined experimentally that the preheating of spray water affects the efficiency of droplet evaporation. The results of experiments proved the feasibility of using water from natural reservoirs without prior preparation for wildfires elimination.

Furthermore, the implementation of investigations presented in this work allowed participants to develop a research base, publish two articles in journals indexed by the leading database of scientific publications. We took part in two international conferences and established scientific contacts with scientists working on this subject, thus, raising research and professionally oriented communicative competence.

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