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Suppression of forest fuel thermolysis by water mist

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ABSTRACT

The processes involved in the suppression of thermolysis in typical forest fuel (mixtures of birch leaves, asp branches, spruce needles) have been experimentally researched. The suppression was achieved by exposing forest fuel (FF) to water mist with different drop sizes. The drop radius was adjusted in the range between 50 μm and 500 μm. The spray intensity ranged from 0.01 to 0.065 $l/(m^2\,s)$. The experiments were performed on a simulated fire source: an ad-hoc cuvette (100 mm in diameter, initial sample thickness 60 mm) where the FF sample was placed. The times necessary for complete FF combustion and the times necessary for suppressing the thermolysis of FF with water mist have been determined. It has been shown that the times of FF thermolysis suppression with fine aerosol are significantly shorter as compared to using a large-drop flow with the density identical to that of fine mist. The dependences between the water evaporation area in the combustion zone and the typical sizes of injected drops at identical spray density have been determined. The relation of energy spent on water evaporation and the heat accumulated in the combustion zone has been determined. The physical principles of a more efficient use of fine water mist for suppressing FF thermolysis (at constant spray density) have been determined. The conditions have been determined, under which a large-droplet mist can be used efficiently in gas-vapor-drop fire suppression technologies.

1. Introduction

Phase transformations in the *liquid drop – gas medium* system are traditionally regarded as one of the most popular areas of research in drop hydrodynamics and thermal physics. We can conclude this by evaluating how many relevant works are published in international highly rated periodicals each year (for example, by searching Scopus and Web of Science databases). High interest towards such processes is due to a wide variety of applications that span many spheres of human activities (thermal and flame cleaning of water, heat exchangers, air conditioners, cooling and microclimate systems, surface treatment, defrosting granular media, fuel combustion and fire extinguishing systems, etc.).

Modern understanding of the phase transformations of liquid drops in gas media has been formed on the basis of now widely recognized understanding by Ranz and Marshall, which is currently actively developed in works by M.C. Yuen, L.W. Chen and M. Renksizbulut [1–3]. However, the experimental and theoretical research in the last decade (in particular, [4–7]) has shown that physical understanding (and the respective models) [1–3] has limitations in terms of temperature ranges (normally, from 300 K to 600–700 K), for which we can obtain the evaporation process characteristics that are in satisfactory compliance with the experimental data. For gas temperatures above 1000 K, adequate phase transformation models (i.e. those allowing for the prediction of phase transformation rates and complying with the experimental data with the deviations at least not exceeding 10–20%) have not yet been developed. The main reason for this is the absence of reliable experimental data. Meanwhile, there is an abundance of potential applications [8–11] for such temperature ranges in the *liquid droplet – gas medium* systems: fuel ignition in combustion chambers; thermal and flame cleaning of water; polydisperse fire suppression; defrosting granular media; treatment of power equipment surfaces exposed to heat; coolants based on smoke gases, droplets and water vapor; evaporating or burning off contaminants from multi-component slurries, etc.

From the above, one of the most complex and important uses (in terms of environmental and overall impact on humankind) is the suppression of major fires (especially forest fires) using efficient high-temperature gas-vapor-droplet technologies. Unfortunately, as of yet, there is no science-proven theory of forest fire suppression [12–14]. Several models of fire break-out prediction and fire spread exist; however, there is no common theory of effi-

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Nomenclature

C_f	FF heat capacity, J/kg K
C_v	water vapor heat capacity, J/kg K
C_w	water heat capacity, J/kg K
d_f, h_f	diameter and height of cuvette used to house FF samples, m
m_{f0}	initial FF sample mass, kg
m_w	water mass, kg
L_f	heat effect of FF thermolysis, J/kg
N	number of droplets evaporating near FF surface
Q_f	heat accumulated in the FF layer undergoing pyrolysis, J
Q_e	aggregate vapor generation heat, J
Q_{e1}, Q_{e2}, Q_{e3}	aggregate vapor generation heat values calculated per unit time (1 s); calculated for the entire thermolysis suppression time t_e; assuming that all the water involved has been evaporated, J
Q_t	energy spent on FF thermolysis, J
Q_v	heat spent on water vapor heating, J
Q_w	heat spent on water heating, J
R_d	initial droplet radius, mm
S_f	area of cuvette cross-section, m^2
S_e	total (aggregate) area of water evaporation surface, m^2
S_v	area of measurement tank surface, m^2
t	atomization duration, s
t_b	time of complete combustion of FF sample, s
t_e	time of FF thermolysis suppression, s
T_f	temperature in the FF layer, K
T_{mf}, T_{if}	maximum and minimum (initial) FF temperatures, K
T_{mv}, T_{iv}	maximum and minimum (initial) water vapor temperatures, K
T_{mw}, T_{iw}	maximum and minimum (initial) water temperatures, K
U_d	initial droplets movement rate, m/s
U_v	linear water vapor movement rate near the evaporation border (calculated from the ratio between the evaporation rate and water vapor density), m/s
V_f	FF sample volume, m^3
V_e	volume of water spent on suppressing the model fire source in the FF, l
V_v	volume of water that was deposited in the measurement tank, l
W_e	evaporation rate, kg/m^2 s
ρ_f	FF sample density, kg/m^3
ρ_v	water vapor density, kg/m^3
μ_w	specific water flow rate of the respective atomizing nozzle, l/s
ξ_e	spray density, l/m^2 s

cient fire suppression. Quite a lot of empirical data are known; those allow for creating relatively efficient fire suppression systems for specific geographic regions only and for a very limited set of fire spread conditions. Apparently, these are the factors that are behind the low efficiency of forest fire suppression throughout the world [12–14].

There are quite many criteria of efficient fire suppression (fire spread rate, change in the size of fire source, heat release, flame height, etc.). Most likely, the most well-substantiated criteria here are the conditions that ensure that the fire source is eliminated within a pre-defined time and at a known flow rate of suppression substances (for example, water). However, for different fire types, there are no specific values of required volumes of water or suppression times that would be internationally recognized as reference values (i.e. sufficient for fire suppression in specific conditions). Normally, the amount of water used for fire suppression is not recorded. That is why specific approaches and technologies are evaluated only by the result, i.e. whether the conditions for extinguishing the fire source have been achieved.

As of late, based on the experimental [15,16] and theoretical [17,18] research, a hypothesis has been put forward; according to it, traditional approaches to fire suppression that envisage the drop off of large volumes of water into the fire zone have low efficiency in terms of spent fire suppression liquids (for example, water); only 7–15% of the mass of the water dropped is spent on suppressing the fire source. The rest of the water trickles through the ground so it does not affect flame spread rate in any way. These conclusions have become a basis for the fundamental research [15–18] aimed at finding optimal conditions and parameters of water delivery into the fire zone.

For model seats of fire (corresponding to the heat output of ground and crown fires [19]) optimal ranges of droplet sizes and concentrations in the water mist flow have been determined; also, the conditions of mist injection into the high-temperature (flame) zone of the fire have been determined [15,16]. It has been shown [15,16] that when droplet size is less than 300 μm then efficient fire suppression conditions can be provided for fire sources with an area less than 1 m^2. From the results of basic experimental research, it has been substantiated [15,16] that the above conditions can be attained by virtually complete evaporation of water droplets fed into the fire zone. Also, experiments [15,16] have been conducted with known combustible and highly flammable liquids as well as forest fuel. The temperature range was 800–1300 K (corresponds to a large group of typical major fires including forest fires). It has been substantiated [15,16] that efficient fire suppression requires intense temperature reduction in the gas medium above the fire source. Here the fineness of the droplets in the flow plays the key role as compared to the traditional parameter that fire fighters assume as the key one: the spray density. The experiments in [15,16] would be logically concluded with further experiments where we would determine the impact of water droplet size on the characteristics of the suppression process of the thermolysis of typical flammable wood materials. Experiments are required where water flow rate would be controlled by means of stable spray density and variable droplet size. Such research would allow for rejecting the hypothesis that the more water is delivered to the fire zone, the better (so, the need for rational water spending would be substantiated). Practice, however, is much different, and there are several reasons to that end [12–14]: from insufficient amounts of water in the vicinity of the fire zone (i.e. it may be difficult to find bodies of water for airborne vehicles to collect water and deliver it to the fire zone) to the negative impact of water vapors on the suppression process (water vapors are among basic greenhouse gases and hence are good heat radiation absorbers).

The purpose of this work is to experimentally research the processes of the suppression of forest fuel thermolysis by water mists with varying droplet sizes.

2. Experimental methods and procedures

The scheme of the setup used in the experimental research is provided in Fig. 1 (its basic components are similar to benches [15,16]).