Experimental evaluation of the effectiveness of water mist automated fire extinguishing systems for oil transportation

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Abstract. Experimental investigation of regularities of carryover of water mist droplets (radius of 50 – 500 μm) by high temperature (500 – 1800 K) products of combustion of typical petroleum products (oil, gasoline, kerosene, etc.) was carried out. The panoramic optical methods and high-speed hardware and software systems were used. Speeds of droplets after mixing with oncoming high temperature gases were determined. Conditions of continuation of droplets movement through combustion products with preservation of initial trajectory in spite of intensive evaporation and braking were found. The predictive evaluation of effectiveness of water mist use for extinguishing of fires involving oil and typical petroleum products.

1. Introduction

Modern technologies of fire extinguishing using water mist, water spray, water curtain and other variants of applications of vapor-droplet aerosol have sufficiently limited implementation [1–3]. Especially if the fires have high spread rate, high flame temperature and high heat flow. These particularly include fires involving oil and petroleum products [4]. As a rule, foam of different expansion rate is used to suppress such fires. Such foams are not always effective and are expensive. Therefore, it is necessary to study the possibilities of application of vapor-droplet water aerosol with the most simple content for extinguishing such fires.

One of the main reasons and possible difficulties for the use of vapor-droplet water sprays to extinguish fires with high speed distribution and high heat flows is carryover of droplets. In the works [5, 6] the features of turning and next carryover of water droplets by flow of high-temperature products of kerosene combustion were studied. The typical values of velocities of water droplets, which they have after the contact with the flame were determined. The conditions under which the droplets can maintain the initial direction of motion, in spite of braking by the combustion products and intensive evaporation were determined. To determine the conditions of applicability of the water vapor-droplet aerosols for the extinguishing of fires with typical petroleum products (particularly kerosene) it is necessary to have experimental data on the macroscopic regularities of evaporation and carryover of droplets of such aerosols. Therefore, it is advisable to develop the understandings [5, 6] for the high temperature combustion products of oil and several typical liquid petroleum products.

The purpose of the article is experimental investigation of macroscopic regularities of carryover of water mist droplets by high temperature combustion products of several widely used petroleum liquid products.

2. Experimental setup and research methods

During the experiments, we used a setup with elements, which are similar to the used in the works [5, 6]. The basic elements of the setup are: high-speed camera *1* (figure format – 1024 × 1024 pixels, the frame frequency up to $6 \cdot 10^5$ per second); *2* – cross-correlation digital camera (figure format – 2048 × 2048 pixels, the minimum delay between two serias shots – not more than 5 ms); double pulsed solid-state laser *3* with active area "YAG" and neodymium additives (wave-length is 532 nm, minimum energy in impulse is 70 mJ, maximum impulse time is 12 ns, recurrence frequency is 15 Hz); synchronizing processor *4* supporting modes of internal and external launch (signal sampling is not more than 10 ns and supporting modes of internal and external launch).
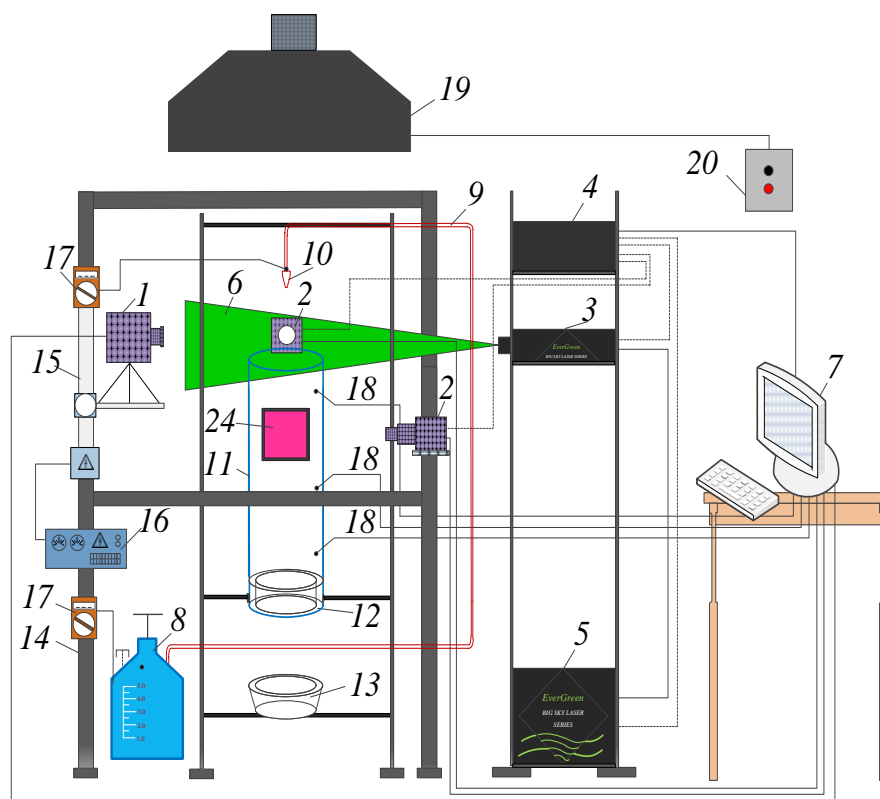

Figure 1. A scheme of experimental setup: *1* – high-speed camera; *2* – cross-correlation digital camera; *3* – double pulsed solid-state laser; *4* – synchronizer of PC, cross-correlation digital camera and laser; *6* – light "pulse"; *7* – PC; *8* – vessel with experimental liquid; *9* –channel of experimental liquid supply; *10* – dosing device; *11* – cylinder of quartz glass; *12* – hollow cylinder with combustible liquid in internal medium; *13* – trap; *14* – mount; *15* – motorized pointing device (MPD) to move the camera; *16* – power supply unit MPD; *17* – digital multimeters; *18* – thermocouples; *19* – replacement exhaust system; *20* – switching on and off board of replacement exhaust system.

The methodology of the experiments included several steps:
- vessel *8* was filled with preliminary prepared water;
- dosing device *10* was connected to the output of the vessel *8* through the channel *9*. The dosing device *10* are configured depending on the required parameters of the flow of liquid (special metal nozzles, generating polydisperse stream of water mist droplets were used in the experiments);
- dosing device *10* was installed on the mount *14* 0.5 m above the top face of the cylinder *11*;

- depending on the type of experiment the height of installation of cross-correlation digital camera *2* and laser *3* was chosen (in the case of application of PIV and IPI methods the height of installation of the laser was chosen so that the optical axis of the camera and plane light «pulse» *6* of laser intersect at an angle of 90 degrees; in the case of SP methods in front the camera the stroboscopic light source was set. It was the screen connected to the laser *3* by means of light guide. The height of installation of the laser is not important in this case);

- calibration of measuring system was carried out (the scale coefficient and the cross-correlation optical zoom of the camera *2* were determined), and also set of the "waist" and the angle of inclination of the light "pulse" *6* of the laser *3* was executed;

- the base of the hollow cylinder *12* was filled with combustible liquid (about 250 ml), which was ignited before the experiment;

- after 5 minutes (the time required for heating of the inner cavity of the cylinder *11* to the required temperature) on the PC *7* the specialized software was run (realizing optical diagnostic methods "Particle Image Velocimetry" (PIV), "Stereoscopic Particle Image Velocimetry" (Stereo PIV), "Particle Tracking Velocimetry" (PTV), Interferometric Particle Imaging (IPI) and "Shadow Photography" (SP)) [7], the dosing device *10* was turned on and the recording of video with droplets of working fluid was carried out;

- the values of velocities and the sizes of water mist droplets were calculated by the PC *7* by means of special software.

The most widely used liquid petroleum products were used for the experiments as combustible liquids: gasoline (RON 92), kerosene (TS-1), acetone (technical, GOST 2768-84), alcohol (ethyl synthetic, GOST 52574-2006), oil (Chayandinskoye condensate field exploration well 75 with ρ=667 g/l). The products combustion temperature in the cylinder channel *11* was controlled in three points of the channel (0.15 m, 0.5 m, 0.85 m) on its symmetry axis using the a chromel-alumel thermocouples (the range of temperature measurement is 273–1373 K, the measurement error is ± 3.3 K).

The water temperature was controlled in two points (in the vessel *8* and in the inlet of dosing device *10*) using two chromel-copel thermocouples (the range of temperature measurement is 273–473 K, the measurement error is ± 1.5 K), and was 298–300 K.

Sizes (radiuses) of water droplets R_m, and velocities of droplets U_m and combustion products U_g were accepted as objective function as in [3, 5, 6].

IPI and SP methods were used to measure the sizes of water mist droplets. IPI method based on measuring the droplet diameter using the distance between the strips on the interference pattern, which was formed by light being reflected and once refracted by droplet. Droplets were illuminated by the light "pulse", the interference pattern was observed for all droplets in the measuring area. Next, using the algorithm "IPI Kit" the droplet sizes were determined. SP method is based on registration of the shadow pictures of an object having a refractive index that is different from its environment. Special screen connected to the laser *3* by means of light guide was placed in front of the camera behind the droplet flow. The cross-correlation digital camera with the colour filter recorded the shadow images of water droplets. Post-processing of images using series of filters and algorithms allowed to determine the droplet size.

PIV, Stereo PIV, PTV methods were used to measure the velocities of the droplets. PIV method was used to estimate the velocities of high-temperature gas flow. These methods are based on determining the movement of special particles – "tracers" during a fixed time interval (the time between the laser flashes). Special polyamide fluorescent particles (particle size is 1–5 microns) were put into water as the "tracer" particles immediately before the experiment. Application of PIV and Stereo PIV methods allowed obtaining averaged two- and three-component fields of the gas flow and droplet flow. The use of PTV allowed determining the velocity of each droplet in the flow.

The final decision in the choice of methods of video image processing was taken from the preliminary analysis of a group of captured video. The main attention was paid to parameters such as

noise in the image, the apparent size of the droplets in the stream, the droplet concentration, the movement of "tracers" during the time between laser flashes.

A hardware-software complex based on high-speed video camera "Phantom" and software "Tema Automotive" [8] was used for additional assessment of velocities and tracks of moving water mist droplets under their mixing with high-temperature gas flow. The flow of droplets was recorded by high-speed video camera *1* with recording frequency is not less than 10^4 frames per second. Video processing with the use of algorithms "Correlation" and "Circular Symmetry" [8] allowed to visualize track of movement for each droplet in the registration area as well as to determine the velocities of their movement.

Systematic errors of determining of the velocities U_m and U_g were about 0.005 m/s, of the sizes R_m were about 10^{-5} m.

3. Results and discussion

Figure 2 shows a typical videogram at the moment of mixing the droplet flow with the counter gas flow (left) and the corresponding velocity field (right). As can be seen from figure 2, all velocities (of droplets and gases) are close to zero at the interface "water droplets – high temperature gases". Significant deceleration, and the subsequent reversal and entrainment of water mist droplets take place exactly at the interface of two medias. However, as it has been found in [5], the initial dimensions R_m of droplets considerably affect to the braking and subsequent reversal of water droplets in the stream of high-temperature gases. For example, figure 2 shows, that relatively large droplets are lower than a pronounced interface "water droplets – high temperature gases" while above it a significant set of smaller droplets, which were not able to overcome the counter resistance is observed.
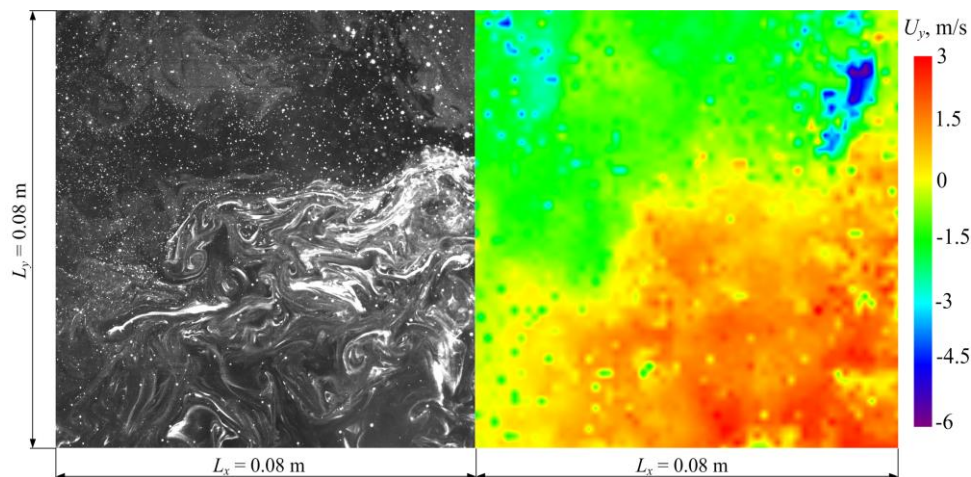

Figure 2. Videogram and velocity field at the moment of mixing the flow of water mist with a counter flow of high-temperature gases.

The dependences of relative velocities of water droplets on the absolute velocities of the counter gas flow were constructed for three typical combustible liquids: gasoline, acetone and oil (figure 3). It was made for analysis of macroscopic regularities of carryover of water mist droplets by high temperature products of combustion of typical combustible products.

To do this, the droplets in flow of water mist (as in [3, 5]) were divided into four groups in accordance with the sizes. After that for each group of droplets the experimental points were found, which later were used for approximation curves construction.

Analysis of figure 3 shows that small droplets with sizes R_m=0.03–0.1 mm completely stop at high velocities U_g of oncoming gas flow from 0.3 m/s to 0.7 m/s. These data are in good agreement with the results of [5], where water droplets of similar size were completely stopped and unfolded to the opposite direction in the combustion products of kerosene at the $U_g \approx 0.3$ m/s.
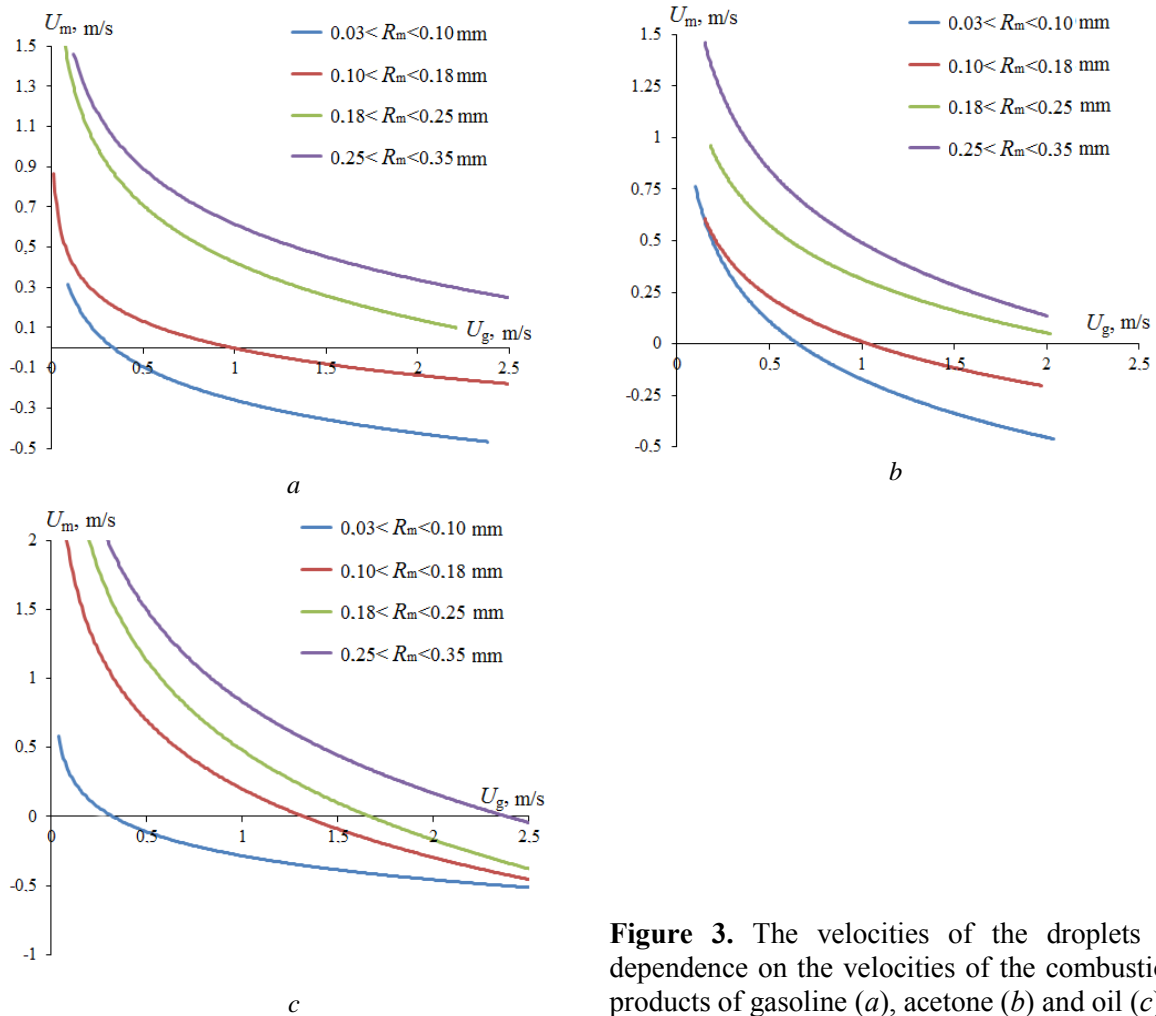
Figure 3. The velocities of the droplets in dependence on the velocities of the combustion products of gasoline (*a*), acetone (*b*) and oil (*c*).

Droplets with sizes R_m=0.01–0.18 mm fully turn during their motion through products of combustion of gasoline and acetone even at velocities of the oncoming gas flow U_g≈1 m/s. The droplets of the same size in the combustion products of oil change their tracks to the opposite at velocities of the oncoming gas flow U_g≈1.3 m/s. To explain this phenomenon it is necessary to pay attention to the temperature of the combustion products of fuels. Table 1 shows the temperature distribution of the combustion products in a cylindrical channel *11* for the 4 flammable liquids.

Table 1. Temperatures (T_f ± 15 K) of the combustion products in cylindrical channel.

The position of the thermocouple relative to the base of cylinder *11*	0.1 m	0.3 m	0.5 m	0.7m	1 m	1.5 m
Gasoline	1906	1540	712	615	475	397
Acetone	1744	1140	832	710	412	384
Kerosene	1738	824	514	485	376	348
Oil	1139	634	506	454	372	339
Alcohol	1105	560	428	404	366	324

The experiments have shown that the highest temperature of the combustion products belongs to gasoline. Its maximum temperature reaches to 1906 K. The acetone and kerosene burns with a lower intensity, their temperatures do not exceed 1744 K and 1738 K respectively. These temperatures are

less by 150–200 degrees than the temperatures of the gasoline combustion products. Oil and alcohol have the lowest temperature of the combustion products which does not exceed 1150 K.

It follows that the temperature of the oncoming gas flow has a great influence on the degree of braking of water droplets. Droplets significantly slow down during intensive evaporation (due to intensive mass loss during vaporization). The more the temperature of the surrounding gas environment, the more rapidly drops brake. These results coincide well with the results of [6], where the conditions of braking and evaporation of sequentially moving drops were analyzed. The temperature of the combustion products of oil is much lower (about 600–800 K) than for gasoline and acetone, therefore large velocity U_g are required (figure 3) for complete stop and turn of water droplets in high temperature gas flow.

Relatively large droplets of water mist (figure 3) is completely stopped and deployed at gas flow velocities are even more than 2–2.5 m/s. That can be explained by the fact that the drops with $R_m > 0.2$ mm evaporate much more slowly than small droplets [3, 5, 6]. Thereby large velocities of oncoming gas flow are required.

After comparing the received data with the results of [3, 5, 6], it is possible to predict the track of the water mist droplets and share of their evaporation during movement in oncoming high temperature combustion products. Experiments have shown that droplet with $R_m < 0.2$ mm are practically completely deployed further input to the space of high-temperature combustion products, without going a distance even 0.2 m. Larger droplets $R_m = 0.2$–0.5 mm are capable to penetrate into the combustion area and almost completely evaporate.

In works on the theme of fire, it is traditionally emphasized [1–4], that fire extinguishing of liquid combustible substances by water droplet flow is possible and necessary, but the liquid must be properly shredded. Different sources give different data about optimal droplet size for the extinguishing of fires of flammable liquid substances (from 100 to 400 microns). These droplets sizes depend on many factors: the flash point of the substance, the area and height of the fire, and others. But the majority of the sources said that for the effective extinguishing droplets must evaporate completely during movement through the flame. Thus, the results of this study can expand the understanding of the modern technologies of fire-fighting and help in the selection of the optimal parameters of water spraying for fire extinguishing at oil and gas facilities. Also, these results may contribute to the development of the theory of two-phase gas vapor-droplet and multiphase systems.

4. Conclusions

The experiments have shown that for typical oil and all considered liquid petroleum products the conditions of entrainment of water droplets by combustion products are typical. The effectiveness assessment of the use of water mist (droplet radius is 50–500 microns) for suppression of oil and petroleum products burning have shown that the main disadvantage of this approach is quite intense carryover of droplets by high temperature flow of product combustion. The main advantage of this approach is almost complete water evaporation, i.e. full involvement of water in the combustion zone.

References
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