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Characteristics of Evaporation and Entrainment of Spray Flow Droplets in High-Temperature Oil Combustion Products: Insight into Academic Research Experience

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Abstract

This paper investigates experimentally the macroscopic laws of the evaporation and entrainment of sprayed water droplets (the initial radius from 50 µm to 500 µm) in high-temperature (from 700 K to 1800 K) typical petroleum combustion products (gasoline, kerosene, industrial alcohol), as explored in academic context. The studies have been performed using optical methods PIV, PTV and SP and specialized software "Tema Automotive". The conditions have been defined for the complete evaporation of water droplets, as well as their braking and entrainment by combustion products. The difference between these conditions for different petroleum combustion products has been pointed out.

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Keywords: Petroleum products; flames; fires; extinguishing; high-temperature combustion products; spray water droplet flows; droplets; evaporation; entrainment.

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1. Introduction

The most common method to extinguish fires involving oil and petroleum products is fire suppression by fire-fighting foam of different multiplicity. However, this technology is quite costly. As a rule, specialized additional

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plants, reservoirs and staff training system are required for its implementation. Furthermore, frequently conducted assessments on the efficiency of such systems are not optimistic. The foam acts as a blocking buffer layer between the combustion zone and the ambient oxidant. Theoretical estimates (Kuznetsov & Strizhak, 2014; Strizhak, 2013) suggest that a water-steam cloud may be used instead of the foam. Moreover, the storage and transportation of water do not require large expenditures in comparison with the foam. Previous works (Volkov, et al., 2014a; Volkov, et al., 2015) reported that fires involving oil and petroleum products are characterized by high temperatures and intense emission of combustion products. Under such conditions, it is quite difficult to generate steam clouds with desired characteristics. It is advisable to conduct special experimental studies on the conditions of the complete evaporation of droplets from such clouds, as well as their entrainment by combustion products from some of the most typical liquid petroleum products. Our previous experiments (Volkov, et al., 2014b; Volkov, et al., 2015; Vysokomornaya, et al., 2014) demonstrated that this problem can be solved with the help of modern panoramic optical methods, such as PIV (Keane, & Adrian, 1992; Simo Tala, et al., 2013), PTV (Damiani, et al., 2014), IPI (Bilsky, et al., 2011), SP (Akhmetbekov, et al., 2010) and others. It is also necessary to perform continuous tracking of moving droplets under the conditions of intensive phase change. Experiments (Janiszewski, 2012) showed that this task can be performed using software "Tema Automotive".

Among the scientists involved in the study of the designated problem, there is professor P. A. Strizhak, engineer R. S. Volkov 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 investigate experimentally the characteristics of evaporation and entrainment of spray flow droplets in high-temperature combustion products of typical petroleum products. Experiments were performed to define the basic laws of phase transformations and heat and mass transfer for the drip water flow moving through the flames of oil and petroleum products.

2. The experimental setup and methods

The experimental setup described in Fig. 1 was similar to facilities that we used to study droplet evaporation (Volkov, et al., 2014a; Volkov, et al., 2015; Vysokomornaya, et al., 2014). The facility is integrated around subsystems: high-speed video camera *1* with the resolution of 1280×800 pixels, frame rate – up to $6 \cdot 10^5$ fps; cross-correlation video cameras *2* with the resolution of 2048×2048 pixels, the minimum delay between two successive frames – no more than 5 μs; double-pulsed laser *3* based on 2 YAG rods with the wavelength of 532 nm, pulse energy – no more than 70 mJ, pulse duration – no more than 12 ns; repetition rate – no more than 15 Hz; synchronizing processor *4* with signal sampling no more than 10 ns, modes of internal and external start.

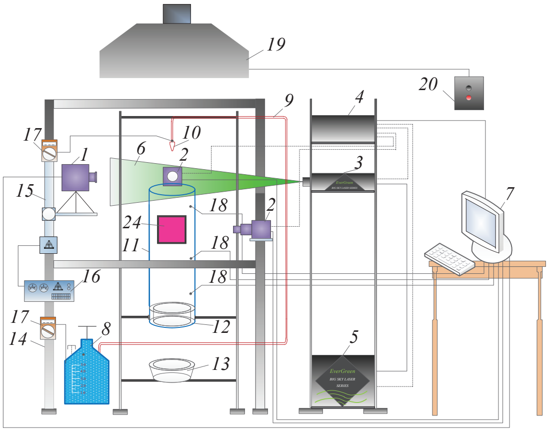


Fig. 1. Scheme of experimental setup: *1* – high-speed video camera; *2* – cross-correlation video camera; *3* – double-pulsed laser; *4* – synchronizer for computer, cross-correlation cameras and laser; *5* – laser line generator; *6* – laser line; 7 – personal computer; *8* – water tank; *9* – water supply channel; *10* – sprayer; *11* – quartz tube; *12* – hollow cylinder with flammable liquid; *13* – water catcher; *14* – framework of experimental setup; *15* – motorized pointing device for camera; *16* – power supply for motorized pointing device; *17* – digital multimeters; *18* – thermocouples; *19* – exhaust hood; *20* – remote on/off switch of exhaust hood.

The methodology of the experiments included several stages:

- a water tank *8* was filled with water;
- a sprayer *10* was connected to the output of the water tank *8* through channel *9*; the sprayer was configured according to the required parameters of sprayed water (in the experiments, special metal nozzles were used that generated polydisperse flow of water mist droplets);
- the sprayer *10* was fixed on a frame rack *14* at the height of 0.5 m above the top face of cylinder *11*;
- the installation height of a cross-correlation camera *2* and a laser *3* was chosen depending on the type of experiment (in the case of measurements by methods PIV and PTV, the camera and the laser were fixed at such height that the angle between the camera optical axis and a laser line *6* was 90° in the observed area; in case of using a method SP, the camera was set up opposite to a strobe light – a special diffuse screen connected to the laser *3* via optical fiber);
- the measuring system was adjusted and calibrated (the scale factor and the optical zoom of the cross-correlation camera *2* were determined); the angle of the laser line *6* and its “waist” were established (for the method SP, the power of each laser modulator was adjusted to obtain the necessary contrast of shadow droplet images);
- the base of a hollow cylinder *12* was filled with liquid petroleum products (about 250 ml); the ignition of flammable liquid was initiated before the experiment;
- when the cylinder *11* was heated inside to the desired temperature (after 5 minutes), specialized software run in the computer *7* (implementing optical diagnostic techniques “Particle Image Velocimetry” (PIV), “Particle Tracking Velocimetry” (PTV) and “Shadow Photography” (SP)) (Akhmetbekov, et al., 2010; Bilsky, et al., 2011; Damiani, et al., 2014; Keane & Adrian, 1992; Simo Tala, et al., 2013); the sprayer *10* was switched and the registration of videograms with liquid droplets was performed (cameras recorded droplets at the input and output of the cylindrical channel);
- the speed and size of water mist droplets were calculated using obtained video recordings in the computer *7* by special software and specialized data processing algorithms.

The most widely used liquid petroleum products were chosen as flammable liquids for our experiments: gasoline (92 octane), kerosene (TS-1), industrial alcohol (synthetic ethanol). Chromel-alumel thermocouples (the temperature range 273–1373 K, measurement error ±3,3 K) were installed to monitor the temperature of combustion products in three points of the cylindrical channel *11* (0.15 m, 0.5 m, 0.85 m) on its axis of symmetry. Type L thermocouples (the temperature range 273–473 K, measurement error ±1,5 K) were installed to monitor water temperature in two points (in the water tank *8* and at the input of the sprayer *10*). The water temperature ranged from 298 to 300 K.

The sizes (radius) R_m and velocities U_m of water droplets, the velocities of combustion products U_g were chosen as objective functions, as in studies (Volkov, et al., 2015; Volkov, et al., 2014b).

The sizes of water mist droplets were measured by the method SP. The method SP is based on the registration of an object shadow photography with a refractive index that is different from its environment. The cross-correlation camera with a predetermined color filter recorded the shadow images of water droplets. Subsequent image processing was performed using a series of filters and algorithms.

The velocities of droplets were measured using methods PIV, PTV. The estimation of the velocities of high-temperature gas flow was performed using exclusively the method PIV. The estimation of the velocities of droplets was performed using PIV and PTV. These methods are based on determining the pathway of polyamide particles added to water as “tracer” particles (particle size – 1–5 μm) immediately before the experiments. The final decision in choosing the method for image processing (PIV or PTV) was made according to the results of preliminary image analysis. The main attention was paid to parameters, such as image noise, the apparent sizes of droplets in flow, the concentration of droplets, the motion of “tracers” during the time between laser flashes.

A hardware-software complex based on a high-speed video camera “Phantom” and software “Tema Automotive” was used for the additional evaluation of the velocities and trajectories of spray flow droplets, when they mix with oncoming high-temperature combustion products (Janiszewski, 2012). Droplet flow was recorded by the high-speed video camera with a frame rate up to 10000 frames per second. Video processing was performed using algorithms “Correlation” and “Circular Symmetry” (Janiszewski, 2012).

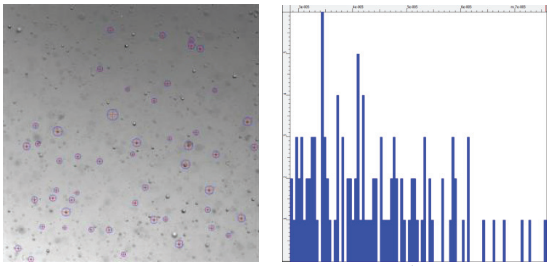
In our experiments, systematic measurement errors of velocities U_m and U_g were 0.005 m/s, and sizes R_m – about 10^{-5} m.

3. Results and discussion

The results of image processing, similar to Fig. 2, indicated data on the concentration and sizes of sprayed water droplets at the input and output of high-temperature gas area (cylindrical channel 11). Comparisons and the subsequent data analysis contributed to a broader insight into the completeness of the evaporation of sprayed water droplets during their motion through high-temperature gas environment. By analogy with studies of sprayed water evaporation (Volkov, et al., 2014a; Vysokomornaya, et al., 2014), a parameter ΔR was considered that showed a decrease in the sizes of liquid droplets falling down through high-temperature gas zone (combustion products) length of 1 m.

This study examines three flammable liquids (gasoline, kerosene and industrial alcohol) used in the experiments. Further analysis and video processing established the dependence of the parameter ΔR from the initial sizes of water droplets in spray flow (Fig. 3).

The character of the curves shown in Fig. 3, a is, in general, similar to results (Volkov, et al., 2014b; Vysokomornaya, et al., 2014) obtained for kerosene combustion products. However, the evaporation characteristics of spray droplet flow in kerosene combustion products are different from that when burning gasoline or industrial alcohol (Fig. 3). Thus, the parameter ΔR takes the greatest value of the droplet size Rm when water droplets pass through gasoline combustion products, and the smallest value – when water droplets pass through industrial alcohol combustion products.



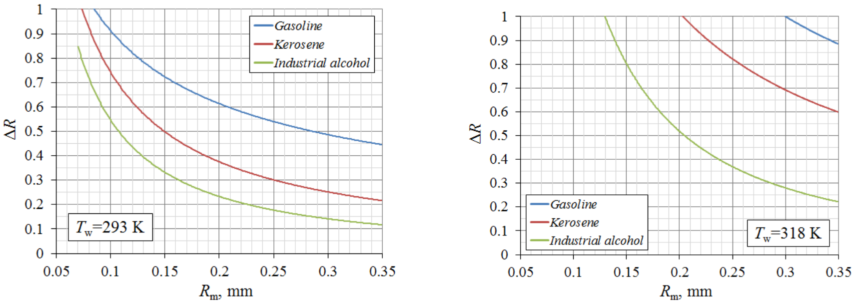
a b

Fig. 2. (a) videogram of spray water droplets with identified droplets; (b) appropriate histogram of droplet size distribution, obtained using a method “Shadow Photography”.

The curve ΔR for kerosene combustion products is in between the gasoline curve and the industrial alcohol curve (Fig. 3, *a*). To explain the difference between ΔR parameters for various flammable liquids, it is appropriate to refer to the temperature of the combustion products of considered flammable liquids T_g. For this purpose, we conducted several series of experiments to determine these temperatures T_g (Table 1).

Experiments (Table 1) showed that the highest temperature of combustion products is for gasoline – 1906 K. Kerosene burns less intensively, its temperatures do not exceed 1744 K and 1738 K, respectively, at the lowest point of the cylinder *11*. This is 150–200 degrees lower than the temperatures of gasoline combustion products. The lowest temperature is typical for industrial alcohol combustion products, it does not exceed 1105 K.

It can be seen that the temperatures of combustion products affect significantly the parameter ΔR. The higher the temperature of the combustion products surrounding droplets, the more intense is their evaporation. Thus, the parameter ΔR is reduced from 1 to 0.45 for gasoline (which is characterized by the highest T_g), when the droplet size varies from 0.05 to 0.35 mm. In turn, the parameter ΔR is reduced to 0.12 for industrial alcohol (which is characterized by the lowest T_g). The parameter ΔR varies from 1 to 0.2 for kerosene under the same conditions.



a b

Fig. 3. The values of the parameter ΔR depending on the initial sizes R_m of water droplets when they pass 1 m in typical oil combustion products at different initial temperatures T_w: (a) T_w=293 K; (b) T_w=318 K.

The nonlinearity of functions $\Delta R=f(R_m)$ (Fig. 3, *a*) can be explained by the nonlinear dependence of the evaporation rate from the temperature of a liquid droplet surface. This means that large water droplets are heated relatively slowly. When the initial droplet size decreases, droplets heat up significantly (several times) faster. Therefore, the evaporation of liquid is intensified. The higher the average temperature of combustion products, the higher is the position of the curves in the diagram on a given interval ($0{,}05<R_m<0{,}35$ mm), and the more linear are these curves (e.g., gasoline curve in Fig. 3, *a*). This feature can be explained by the fact that droplet sizes R_m (observed range – 0.05–0.35 mm) do not almost affect the rate of droplet heating, and hence the evaporation rate at high temperatures (about 2000 K).

Table 1. The temperatures (T_f±15 K) of oil combustion products at different heights.

The position of a thermocouple relative to a cylinder base *11*	0.1 m	0.3 m	0.5 m	0.7 m	1 m
Gasoline	1906	1540	712	615	475
Kerosene	1738	824	514	485	376
Industrial alcohol	1105	560	428	404	366

Besides that, studies established the range of the parameter ΔR for the case when the initial temperature of sprayed water droplets increased during their motion through high-temperature oil combustion products (Fig. 3, *b*). Thus, when the initial temperature of water droplets increased from 293 K to 318 K, their evaporation rate increased significantly. This therefore indicates the increase of the parameter ΔR by 2–3 times (Fig. 3, *b*) and the linear form of the curves. These data correlate well with the results of previous reports (Volkov, et al., 2014; Vysokomornaya, et al., 2014).

The analysis of videograms established the characteristic difference between the velocities of droplets of various sizes during their motion in the counter flow of high-temperature oil combustion products (gasoline, kerosene, industrial alcohol). The rate of water droplets at $R_m<0.2$ mm is 2–3 times lower than that of the larger ($R_m>0.2$ mm) nearby droplets. The velocities of individual droplets in flow become almost equal to zero. This fact suggests that the counter flow of combustion products affects substantially water droplet velocities.

4. Conclusion

The results of experimental studies allowed us to summarize the macroscopic laws of the evaporation and entrainment of sprayed water droplets during their motion through high-temperature combustion products of the most typical liquid petroleum products. It has been shown that droplets less than 0.2 mm evaporate almost completely or carried away without passing flames up to 1 m. The conditions have been predicted that describe the entrainment and complete evaporation of large droplets. The integral characteristics of investigated processes have been established that enable to assess the necessary and sufficient conditions for extinguishing fires involving typical petroleum products by water vapor-droplet clouds.

Along with this, the implementation of investigations presented in this work allowed the participants to develop a research base, which made it possible to get four articles published in journals indexed by the leading database of scientific publications. We took part in three international conferences held in Spain, Italy and USA, and established scientific contacts with scientists working on this subject. In other words, the academic research described made it possible for TPU researchers to get a valuable experience and prepare background for further developments.

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References

Akhmetbekov, Y. K., et al. (2010). Planar Fluorescence for Round Bubble Imaging and its Application for the Study of an Axisymmetric Two-Phase Jet. *Experiments in Fluids, 48*, 615–629.

Bilsky, A. V., et al. (2011). Interferometric technique for measurement of droplet diameter. *Thermophysics and Aeromechanics, 18*, 1–12.

Carriere, T., et al. (2012). Fire Suppression Test Using a Handheld Water Mist Extinguisher Designed for the International Space Station. *42rd International Conference on Environmental Systems*, 17-22.

Damiani, D., et al. (2014). A Particle-Tracking-Velocimetry (PTV) Investigation of Liquid Injection in a DC Plasma Jet. *Journal of Thermal Spray Technology, 23*, 340–353.

Janiszewski, J. (2012). Ductility of selected metals under electromagnetic ring test loading conditions. *The International Journal of Solids and Structures, 49*, 1001–1008.

Janiszewski, J. (2012). Measurement procedure of ring motion with the use of high speed camera during electromagnetic expansion. *Metrology and Measurement Systems, 19*, 797–804.

Karpov, A. I., et al. (2005). Numerical modeling of the effect of fine water mist on the small scale flame spreading over solid combustibles. *Fire safety science: proceeding of eight international symposium, 27*, 753–764.

Keane, R. D., & Adrian, R. J. (1992). Theory of cross-correlation analysis of PIV images. *Applied Scientific Research, 49*, 191–215.

Kuznetsov, G. V., & Strizhak, P. A. (2014). Numerical investigation of the influence of convection in a mixture of combustion products on the integral characteristics of the evaporation of a finely atomized water drop. *Journal of Engineering Physics and Thermophysics, 87,* 103–111.

Simo Tala, J. V., et al. (2013). Investigation of the flow characteristics in a multirow finned-tube heat exchanger model by means of PIV measurements. *Experimental Thermal and Fluid Science, 50*, 45–53.

Strizhak, P. A. (2013). Influence of droplet distribution in a "water slug" on the temperature and concentration of combustion products in its wake. *Journal of Engineering Physics and Thermophysics, 86,* 895–904.

Volkov, R. S., et al. (2014). Evaporation of two liquid droplets moving sequentially through high-temperature combustion products. *Thermophysics and Aeromechanics, 21*, 255–258.

Volkov, R. S., et al. (2015). Experimental investigation of mixtures and foreign inclusions in water droplets influence on integral characteristics of their evaporation during motion through high-temperature gas area. *International Journal of Thermal Sciences, 88*, 193–200.

Volkov, R. S., et al. (2014). The influence of initial sizes and velocities of water droplets on transfer characteristics at high-temperature gas flow. *International Journal of Heat and Mass Transfer, 79*, 838–845.