Experimental study of substandard liquid hydrocarbons spraying by shadow photography method

Anufriev I.S. [1,2], Shadrin E.Yu. [1], Kopyev E.P. [1], Sharypov O.V. [1],
Osintsev Ya.A. [1,2], Mukhina M.A. [1,3]
[1] Kutateladze Institute of Thermophysics SB RAS,
Novosibirsk, Russia
[2] Novosibirsk State Technical University
Novosibirsk, Russia
[3] Novosibirsk State University
Novosibirsk, Russia

1 Introduction

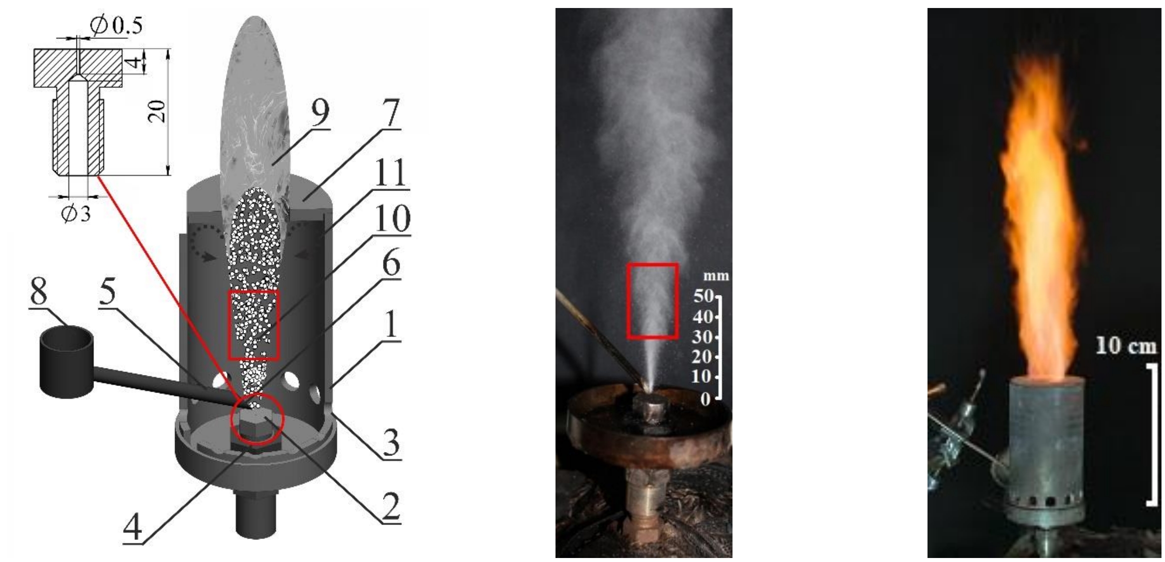
This work is a continuation of research aimed at increasing the combustion efficiency of substandard liquid hydrocarbon fuel based on the method of combustion in a jet of superheated steam developed at IT SB RAS [1]. This method ensures high kinetic and ecological characteristics of the process achieved for the original burners of the evaporative type with steam gasification of products of thermal decomposition of fuel [2]. The next important step for intensification of such fuel combustion is the original method proposed by the authors for creating a two-phase flow, consisting of finely dispersed droplets of fuel and superheated steam as a carrier phase, in a burner [3]. Specificity is that the liquid fuel is sprayed directly by a high-speed steam jet without using a fuel nozzle. This method of combustible mixture forming has significant technical advantages associated with preventing the possibility of coking and clogging of the fuel supply channels, which improve the performance and reliability of the burner. However, the effectiveness of the proposed method depends on the disperse composition of the gas-droplet flow, which determines the intensity of the processes of interfacial heat and mass transfer and, ultimately, the parameters of reaction and composition of the combustion products.

The disperse composition of the gas-droplet flow was investigated by the method of shadow photography when spraying the waste transmission automotive oil by a jet of superheated steam at different operating parameters [4].

2 Experimental setup and techniques

Correspondence to: kopyeve@itp.nsc.ru

The characteristics of the gas-droplet flow (without combustion) were studied on a direct-flow burner with a power of up to 20 kW (Figure 1). Steam flows from the nozzle (Figure 1-a) in the form of a jet, and when liquid fuel flows on this jet, a fine-dispersed gas-droplet flow is formed (Figure 1-b). As a result of jet flow onto the inner plane of the nozzle, a recirculation region is formed in the peripheral zone (Figure 1-a), where ignition is initiated at starting and steam-oil jet ignition is stabilized during operation of the device. At the same time, steam gasification of the products of thermal decomposition of fuel occurs in the combustion zone, which also increases combustion characteristics of liquid hydrocarbons. The resulting combustible mixture of CO and H_2 burns in a flame, mixing with oxygen from the outer atmosphere (Figure 1-c). The flow area of 35x23 mm (marked by the frame in Figure 1-a, b) located in the combustion chamber near the nozzle, where the mixture ignites, is of a particular interest.



(a) (b) (c)

Figure 1. (a) Scheme of the experimental burner: cylindrical housing – 1, steam atomizer – 2, air supply holes – 3, steam line – 4, fuel feed tube – 5, chamfer – 6, nozzle – 7, fuel receiver – 8, flame – 9, steam-oil jet – 10, recirculation zone – 11; (b) visualization of fuel spraying by a jet of superheated steam; (c) characteristic stable combustion in the burner unit by the example of used transmission oil.

The disperse composition of the gas-droplet flow was measured using the shadow photography method. The method is based on recording a shadow photograph of an object with a refractive index different from its surrounding medium. At that, a diffuse light source with uniform spatial distribution of intensity is located behind the studied object (relative to the camera). The focusing plane of the camera lens is in close proximity to the object of investigation (to obtain the greatest clarity of the shadow photo). Digital analysis of the shadow image allows determination of the position and boundary of the object. The scheme of the method is shown in Figure 2.

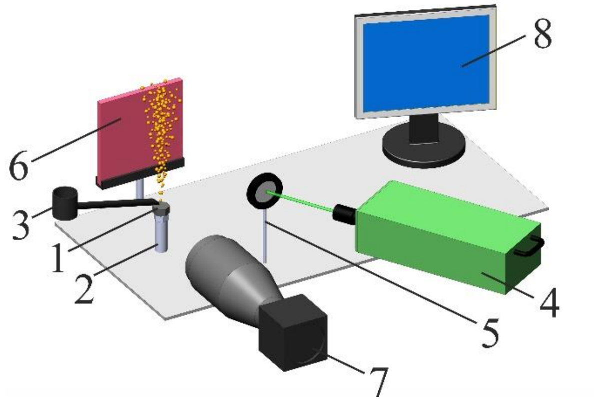


Figure 2. The scheme of experimental setup for studying the characteristics of liquid fuel spraying by a jet of superheated steam: 1 - steam nozzle; 2 - supply of superheated steam; 3 - fuel supply; 4 - pulsed laser; 5 - diffuse glass; 6 - background screen with luminescent coating; 7 - digital camera; 8 - computer.

The "Polis" measuring system was used for the experiments, it included: ImperX B4820-M CCD camera (resolution of 4904 × 3280 pixels, shooting frequency of 3.2 Hz, minimal interframe delay of 200 ns) and Tamron SP AF macro lens with a focal length of 180 mm that allowed the measurements with good spatial resolution (1:1 magnification). A pixel dimension was about 7 microns. A background screen with a rhodamine-based luminescent coating, preliminarily illuminated by a defocused beam of Nd:YAG QuantelEVG pulse laser (wavelength of 532 nm, pulse energy of up to 145 mJ, pulse duration of 10 ns), was used as a light source. To increase the contrast of the shadow photo, a threshold light filter (560 nm), whose transmission bandwidth corresponds to the wavelength of light re-emitted by rhodamine, was used.

3 Results and discussion

In experiments, to reduce a fuel viscosity, the waste oil was heated to a temperature of 40°C. The characteristic shadow photographs of the gas-droplet flow near the steam nozzle are shown in Figure 3. It is seen that at phase interaction along the initial region, the flow has an inhomogeneous structure: there are elongated filamentary structures and large-sized liquid films in the flow (which are split downstream into smaller droplets, including those obtained by steam heating, and the flow becomes homogeneous).

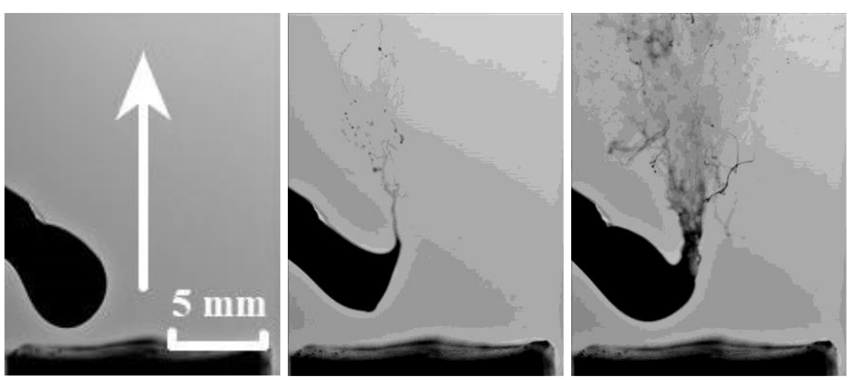


Figure 3. Shadow photographs of a gas-droplet jet when spraying waste automotive oil by a high-speed jet of superheated steam at successive instants (Weber number about 5000, Ohnesorge number about 0.1).

The droplet sizes were measured for different regime parameters, which were chosen to ensure stable combustion in the burner. The range of fuel flow rare F_f = 0.2÷2.0 kg/h corresponds to the permissible power of the burner in laboratory measurements. The range of steam flow rates F_v=0.2÷1.4 kg/h corresponds to the working range of the dosing water pump. The temperature of steam for the chosen regimes varied in the range T_s=150÷550°C (this is caused by the capacity of the laboratory electric steam generator) under the pressure of up to 9 bars.

The "Bubbles Identification" algorithm implemented in the ActualFlow software [5] was used for digital processing of the obtained shadow images. It included the high-pass filtering algorithm for the purpose of delineating the images registered in the photos; algorithm of binarization by a threshold value; and algorithm for determining the position and diameter of spherical droplets.

A series of 100 measurements (200 images) was carried out for each studied regime. During processing, the total particle distribution over all images, normalized to the total number of identified particles, was taken into account.

As a result of image processing, information on the disperse composition of oil droplets under various conditions was obtained (Figure 4). The predominant particle size in all regimes is 10-20 μm, and this is a sufficient condition for efficient combustion of fuel. Dependence of droplet size on steam flow rate at a constant relative steam flow rate $\gamma = F_v/F_f$ is presented in Figure 4-a. According to analysis of results, the particle size depends on parameter γ (Figure 4-a): the fraction of fine particles in the flow (less than 20 μm) decreases with increasing steam flow rate, and the number of larger particles (larger than 20 μm) increases. It can be assumed that at a high steam flow rate, the time of phase interaction reduces, and this decreases the intensity of fuel vaporization by steam. The fuel flow rate (Figure 4-b) and steam temperature (Figure 4-c) have a little effect on a change in the size of oil droplets in the flow.

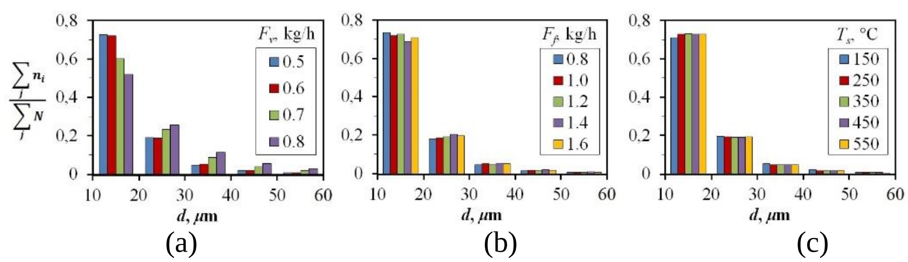


Figure 4. Disperse composition of fuel droplets, formed at spraying the waste transmission automotive oil by a steam jet in the atmosphere: (a) depending on steam flow rate F_v at γ = 0.6 and T_s=250°C; (b) depending on fuel flow rate F_f at F_v=0.6 kg/h and T_s=250°C; (c) depending on steam temperature T_s at F_v=0.6 kg/h and F_f =1.0 kg/h (n_i – number of droplets with sizes of the i-th range in the j-th image, N – total number of droplets identified by the algorithm in the j-th image, j = 1…200)

4 Conclusion

The disperse composition of the gas-droplet flow was studied by the method of shadow photography when spraying the waste transmission automotive oil by a jet of superheated steam at various operating parameters corresponding to stable operation of the studied burner. The predominant particle size in the flow under the studied regimes is 10-20 μm, and this is a sufficient condition for efficient combustion of fuel. It is shown that an increase in steam flow rate leads to an increase in the size of oil droplets. The fuel flow rate and temperature of steam have a little effect on variation in the disperse composition. The obtained experimental data can be used to perform numerical calculations of combustion of liquid hydrocarbons with atomization.

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