Investigation of characteristics of diesel fuel atomization by steam jet

Sharypov O.V. [1], Anufriev I.S. [1,2], Shadrin E.Yu. [1], Kopyev E.P. [1], Leschevich V.V. [3]
[1] Kutateladze Institute of Thermophysics SB RAS,
Novosibirsk, Russia
[2] Novosibirsk State Technical University
Novosibirsk, Russia
[3] A.V.Luikov Heat and Mass Transfer Institute NASB,
Minsk, Belarus

1 Introduction

The problem of effective dispersion of liquid hydrocarbon fuels (including highly viscous fuels) is one of the key aspects in the design of burners. Spraying fuel delivered through a nozzle usually leads to coking, and this reduces reliability of equipment. Therefore, the search and scientific reasoning of the special methods for obtaining a highly dispersed stable gas-droplet flow for efficient mixing of combustible components and oxidizer in the volume of combustion chamber is relevant. A promising method for spraying substandard liquid hydrocarbons based on liquid interaction with a high-velocity gas flow is proposed at Kutateladze Institute of Thermophysics SB RAS [1]. A distinctive feature of this method is the fact that the fuel and atomizing medium (carrier phase - steam) are not pre-mixed with each other: steam is supplied from a nozzle in the form of a jet, and when liquid fuel flows on this jet, a fine-dispersed gas-droplet flow is formed. Since there is no contact between the fuel and nozzle, coking of its surfaces does not occur, which prevents malfunctions. This scheme of fuel dispersion has the prospects for the practical application.

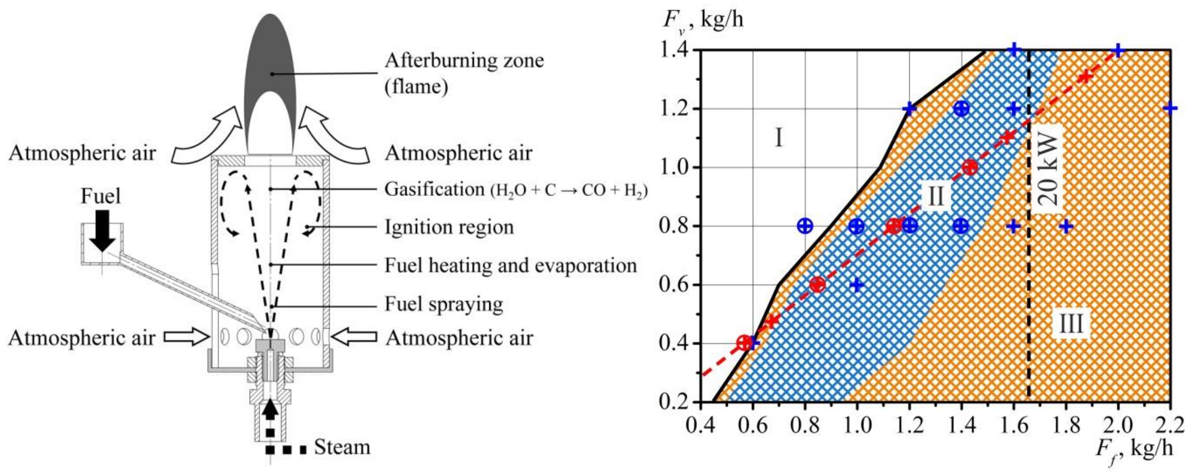
In order to find the optimal regime parameters for the creation and subsequent ignition of the gas-droplet flow, the detailed experimental investigation of the spray characteristics of the studied flow is required (the flow rate and temperature of the carrier phase, ratio of the carrier phase and fuel flow rates, preferred size and concentration of fuel droplets, characteristic time of dispersed phase relaxation).

2 Experimental setup and technique

In this paper, the process of dispersion of liquid hydrocarbons by the jet of superheated steam in a direct-flow burner (without combustion) is studied at the example of diesel fuel. The scheme of dispersion and

Correspondence to: kopyeve@itp.nsc.ru

combustion of liquid fuel is shown in Figure 1-a. Steam flows from the nozzle (diameter of 0.5 mm) in the form of a jet, and when liquid fuel flows on this jet, a fine-dispersed gas-droplet flow is formed. In addition to fuel spraying, superheated steam raises the temperature of fuel droplets, and this intensifies mass transfer and mixture formation, contributing to sustained ignition. At the same time, steam gasification of the products of fuel thermal decomposition occurs in the combustion zone, and like in the case of evaporative burners [2], this increases the combustion characteristics of liquid hydrocarbons. To reduce toxic emissions and increase completeness of fuel combustion, it is important to ensure high homogeneity of the gas-droplet flow, finest crushing of fuel, and high stability of the flame.



(a) (b)

Figure 1. (a) Scheme of combustion in the burner; (b) regime map of the burner (T_s=250°C): I – flame blowout; II – zone of “ecological” stable combustion(experimental combustion efficiency > 96%, content of CO in combustion products < 500 ppm); III – flame with a high content of CO in combustion products (> 500 ppm); «+» – studied regimes («+» – regimes at γ=0.7); ⊕, ⊕ – results presented in the paper.

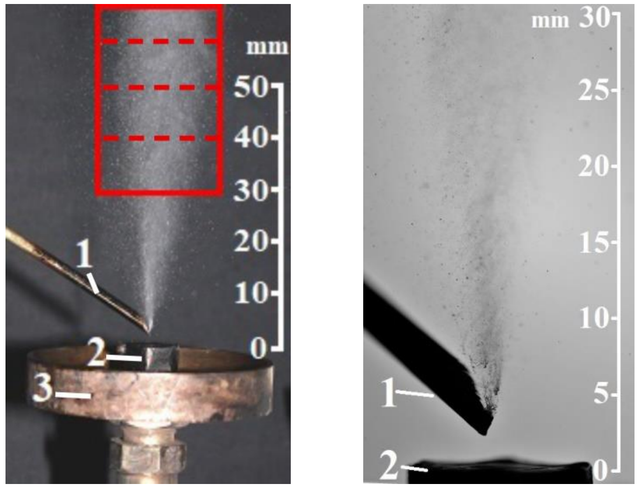
Preliminary studies allowed obtaining a regime map for a given burner design (Figure 1-b). The range of steam flow rates F_v corresponds to the working range of the dosing water pump, and productivity of the laboratory electric steam generator required for steam superheating to predetermined temperature (T_s~250°C). The limits of fuel flow rate F_f correspond to the permissible power of burner in the laboratory measurements. (Relative mass flow rate of steam $\gamma = F_v/F_f$). The temperature of superheated steam in experiments was set constant T_s=(250±10)°C because it was determined previously that a further increase in the degree of steam superheating (at T_s > 250°C) does not affect the combustion of fuel. The steam pressure varied from 3 to 11 bars depending on the values of F_v and T_s, steam superheating $T_s – T_b$ was up to 100°C (T_b is the temperature of saturated steam). The characteristic regimes marked by the symbols on the map (Figure 1-b) were chosen to be studied in this paper.

To study the characteristics of liquid fuel spraying by a steam jet, a contactless optical method for diagnosing flows was used: the method of shadow photography (SP) [3-4]. The SP method is based on recording a shadow photo of an object with a refractive index different from its surroundings. At that, a diffuse light source with a uniform spatial distribution of intensity is located behind the object under investigation (relative to the camera). The plane of camera lens focusing 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 you to determine the position and boundary of the object.

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 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

The photographs of a gas-droplet flow at diesel fuel spraying by a steam jet are shown in Figure 2. It can be seen that a sufficiently dense, uniform mist consisting of fuel microdroplets concentrated mainly within the opening angle of the steam jet (~17°C) is formed as a result of this phase interaction at the initial site. The height of the mixing and ignition chamber of the studied burner is about 90 mm. When measuring droplet sizes, we considered the region at a distance of 30-65 mm from the nozzle edge (Figure 2-a): a uniform gas-droplet flow is formed along 30 mm, and after 60 mm, fuel ignition occurs. At maximal magnification of the lens (1:1), the size of the measuring area was 35x23 mm (the size of one pixel was about 7 μm). Digital processing of the obtained shadow images was carried out using the “Bubbles Identification” algorithm, implemented in the ActualFlow software. This algorithm allows reliable determination of the size of particles, whose images are not less than 5 pixels: the size in one direction is not less than 3 pixels, which corresponds to 21 μm. However, in the flow, there can be the particles of a smaller size with significant concentration, determination of which is a separate task. In addition, the particles with dimensions of <20 μm can be also identified by the algorithm, since during shooting they can get to the pixel boundary, thereby shading many pixels in the image and creating the images larger than the real particle size. Therefore, it is impossible to determine their size accurately, but only the amount in the range of 10-20 microns (according to the parameters chosen at image processing, the particles less than 10 μm were not identified by the algorithm). It is also necessary to note one more feature of measurements: the focusing depth of the lens is about 1 mm, which is 100 times more than the minimal size of the identified particles. This means that in the plane of lens focusing, the particles can overlap each other and stay unrecognized.

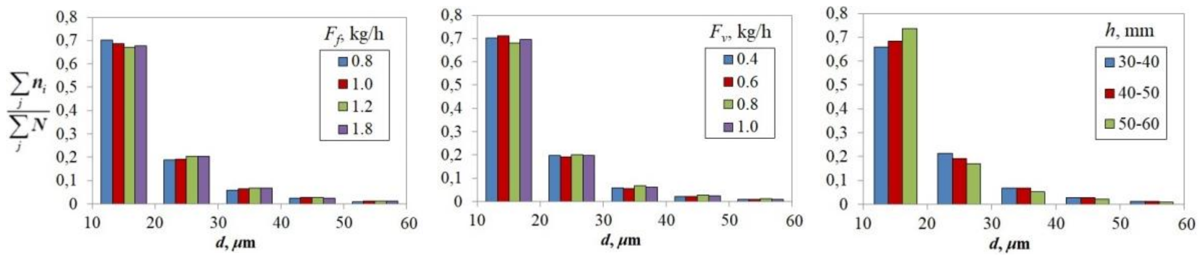


(a) (b)

Figure 2. (a) Photograph of diesel fuel spraying by a steam jet in the burner (the border shows the boundaries of the measuring area); (b) shadow photograph of the gas-droplet flow near the nozzle; 1 - fuel tube, 2 - steam nozzle; 3 - burner base.

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

The results of measurement processing are presented in Figure 3: disperse composition of fuel droplets at a constant flow rate of steam for different flow rates of fuel (a); at constant γ parameter for different flow rates of steam (b); at different distances from the nozzle for one regime (c). According to analysis of Figure 3-a, fuel flow rate (at constant steam flow rate) in the considered range does not significantly influence a change in the disperse composition of the gas-droplet flow. The preferred size of the identified particles in the flow is 10-20 μm. At the same time, the burner combustion regimes (see Figure 1-b) is not associated with a change in the droplet size in the flow and, probably, depends on another parameters not considered in this work: a ratio of fuel and oxidant in the mixture, a limitation of the maximal power of the studied burner. Figure 3-b also shows a weak dependence of droplet size on the relative steam flow rate (parameter γ); the predominant particle size is also 10-20 μm. Analysis of Figure 3-c shows that as the distance from the nozzle edge increases, the number of small droplets (10-20 μm) in the flow increases and the number of larger droplets (> 20 μm) decreases due to evaporation of fuel downstream, and this contributes to more efficient combustion of the fuel.



(a) (b) (c)

Figure 3. Disperse composition of fuel droplets, formed at diesel fuel spraying by a jet of superheated steam in the atmosphere at T_s=(250±10) °C: (a) F_v=0.8 kg/h; (b) γ=0.7; (c) F_v=1.2 kg/h, F_f=1.4 kg/h (n_i – number of droplets with dimensions 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

In this work, the disperse composition of the gas-droplet flow was measured using the shadow method at diesel fuel spraying by a jet of superheated steam in a direct-flow burner (without combustion). The droplet size distributions were obtained in a wide range of regime parameters. It is shown that the characteristic size of the identified droplets in the studied regimes is about 10-20 μm. It was found out that the disperse composition of identified droplets depends little on the fuel and steam flow rates. The boundaries of combustion regimes are not related to a change in the size of droplets. The obtained experimental data are in demand for numerical calculations of combustion of liquid hydrocarbons with atomization.

The work was supported by the Russian Foundation for Basic Research (Project No. 18-58-00025-Bel_a).

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