Investigating substandard liquid hydrocarbons spraying by a steam jet

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Abstract. Using the shadow photography (SP) method and the interferometric method (IPI), a two-phase gas-droplet flow was experimentally investigated when the spent transmission oil was sprayed by a jet of superheated steam. In a wide range of operating parameters, data on the dispersed composition of the steam-fuel jet have been obtained. The dependences of droplet sizes in the flow on the studied regime parameters have been established.

1. Introduction

High-quality fuel dispersion is an important technical task in the development of technologies for the combustion of substandard hydrocarbon fuels, such as waste oils, crude oil, etc. The use of such fuels in spray burners leads to the formation of a large amount of soot and harmful emissions, coking and clogging of spray nozzles, which cause failures in burners’ operation. Therefore, when creating the burners for substandard fuel combustion, it is important to find the optimal solution to these problems by conducting laboratory simulation. Obtaining detailed information about the structure and dispersed composition of the gas-droplet fuel jet using modern optical methods (SP, IPI) \cite{1-3} is important for optimizing the equipment and for the combustion process as a whole.

One of the promising methods of substandard liquid fuel spraying was developed by the staff of IT SB RAS \cite{4} on the basis of interaction of liquid and high-speed gas jet. Its distinctive feature is the lack of contact between the fuel and the surface of the spray nozzle, which prevents from possible coking of surfaces and subsequent failures in operation. The use of superheated steam as a spraying medium also allows achieving high thermal and environmental performance. In order to find the optimal operating parameters (temperature and steam flow rate, fuel flow rate) for the creation and subsequent ignition of the gas-droplet flow, a detailed experimental study of the fuel atomization characteristics by the proposed method is necessary.

2. Experimental setup and technique

In this paper, the atomization of substandard liquid hydrocarbons by a jet of superheated steam in a direct-flow burner (without combustion) is studied by the example of the spent transmission oil. This fuel, as an example of low-grade liquid hydrocarbons with relatively high viscosity (\approx 69 \text{ cSt at 40 °C}) and high content of impurities, is chosen to investigate the performance of spray unit in application to such fuels.

The process of dispersion and combustion of liquid fuels is as follows. The steam flows out of the nozzle (diameter of 0.5 mm) in the form of a jet. Liquid fuel flows freely into its base where it is
atomized by the jet, resulting in a finely dispersed gas-droplet flow. At the same time, superheated steam increases the temperature of the fuel droplets, thereby improving the process of mixture formation and furthering stable ignition. Steam gasification of products of thermal decomposition of fuel also takes place in the combustion zone, which improves the combustion characteristics of liquid hydrocarbons similar to the case of evaporative burners [6]. To reduce toxic emissions and increase the completeness of fuel combustion, it is important to ensure high uniformity of the gas-droplet flow, the smallest possible fragmentation of fuel, and high stability of the torch.

Figure 1. (a) Photo of fuel jet at spraying spent transmission oil by superheated steam jet; (b) Regime map of the burner ($T_s=250^\circ$C): I – flameout; II – zone of “ecological” stable combustion; III – flame with a high content of CO in combustion products ($> 500$ ppm); “+” – studied regimes.

Preliminary studies served to obtain a range of stable combustion modes typical for this design of the burner device (Fig. 1-b). The range of steam flow rates $F_v$ corresponds to the working range of the dosing water pump. Limits of fuel flow rates $F_f$ correspond to the permissible power of the burner in laboratory measurements. The temperature of superheated steam in the experiments varied in the range $T_s = 150..350$ £C. The steam pressure depending on the values of $F_v$ and $T_s$ ranged from 3 to 11 bar, and steam superheating $(T_s - T_b)$ reached 100 £C ($T_b$ – temperature of saturated steam). In the experiments, the waste oil was heated to a temperature of 40 £C to reduce the viscosity and ensure a stable supply. For the study by the methods of SP and IPI in this work, characteristic modes marked on the map by symbols “+” were selected.

To study the characteristics of liquid fuel spray, non-contact optical methods of flow diagnostics were used: the method of shadow photography (SP) [1-2] and the interferometric method for determining droplet diameters (IPI) [1, 3]. The SP method is based on a shadow photo of an object with a refractive index different from its environment. In this case, behind the object under study (relative to the camera) there is a diffuse light source with a uniform spatial distribution of intensity. Digital analysis of the shadow image allows determining the position and boundary of the object. Figure 2 shows a typical shadow photograph of a jet of sprayed oil, processed using special algorithms. The IPI method is based on the registration of defocused droplet images, illuminated by a laser sheet. According to the Mie theory of scattering [3], the light reflected and two times refracted by the spherical surface of the droplet creates interference fringes on the images of droplets. Their frequency directly depends on the diameter of the droplet. Digital analysis of the obtained images allows determining the position and size of the droplets suspended in the stream. This method allows measuring particles with sizes from 10 microns.
Figure 2. Typical shadow picture of the sprayed oil jet. The markers indicate the identified particles.

To conduct experiments by the SP method, the "Polis" measuring complex was used. It included: CCD camera ImperX B4820-M (resolution 4904×3280 pixels, shooting frequency of 3.2 Hz, and minimum inter-frame delay of 200 ns) and a macro lens Tamron SP AF with a focal length of 180 mm, which allowed measurements with good spatial resolution (magnification 1:1). As a light source, a background screen with a rhodamine-based fluorescent coating was used. It was pre-illuminated by a defocused beam of a pulsed Nd:YAG QuantelEVG laser (wavelength – 532 nm, pulse energy – up to 145 MJ, and pulse duration – 10 ns). To increase the contrast of shadow photographs, a threshold light filter (560 nm) was applied. Its bandwidth corresponded to the wavelength of light re-emitted by rhodamine.

For experiments with the use of the IPI method the measuring complex "Polis" was used also. It included: CCD camera ImperX B4820-M and Nikon macro lens with a focal length of 105 mm. To compress the image in one direction, an optical compression unit was used. It was specially designed for the used lens. Pulsed Nd:YAG laser QuantelEVG was applied as a light source.

For digital processing, ActualFlow software with SP Kit and IPI Kit packages was used.

3. Results
As a result of processing images obtained by oil spraying with a jet of superheated steam, the following features have been revealed (Fig. 3). The predominant particle size in the studied regimes is 10-20 µm, which is a sufficient condition for efficient fuel combustion [6] and indicates the advantages of the method used for dispersing liquid fuel.

With changes in fuel flow rate, the dispersed composition remains unchanged (Fig. 3-a). It is an obvious fact, since the liquid spraying under constant influence is determined by the parameters of this liquid and is independent of the flow rate. The steam temperature above 250 °C has no effect on the droplet size (Fig. 3-c): with adiabatic expansion of the steam jet flowing out of the nozzle, its temperature drops sharply and in the measuring area (where the fuel ignites in the burner) it reaches approximately the same value for different initial steam temperatures. Downstream the number of small drops increases (Fig. 3-d), which is associated with the evaporation of fuel.
Figure 3. The dispersed composition of the gas-droplet flow formed by spraying the exhaust transmission motor oil with a jet of superheated steam:

(a) at constant fuel flow rate $F_f = 1.6$ kg/h ($T_s = (260 \pm 10)$ °C) and oil temperature of 40 °C (IPI-measurements);
(b) at constant steam flow rate $F_v = 0.6$ kg/h ($T_s = (260 \pm 10)$ °C) and oil temperature of 40 °C (IPI-measurements);
(c) at constant steam flow rate $F_v = 0.6$ kg/h, fuel flow rate $F_f = 1.0$ kg/h and oil temperature of 40 °C (SP-measurements);
(d) at constant steam flow rate $F_v = 0.6$ kg/h, fuel flow rate $F_f = 1.0$ kg/h and oil temperature of 40 °C ($T_s = (260 \pm 10)$ °C) at different distances from the nozzle (SP-measurements).

$n_i$ is the number of drops with dimensions from the $i$-th range in the $j$-th image, and $N$ is the total number of droplets identified by the algorithm in the $j$-th image, $j = 1...200$.

4. Conclusion

Using the method of shadow photography and interferometric method, the dispersed composition of the gas-droplet flow has been studied at spraying the spent transmission oil by a jet of superheated steam at different operating parameters corresponding to the stable operation of the burner under study. It is shown that the characteristic size of the identified droplets is about 10-20 microns in the whole range of the studied regimes, which is sufficient for efficient combustion of liquid fuel. Steam temperatures above 250 °C do not affect spray performance. The obtained experimental data are in demand for numerical calculations of the combustion processes of liquid hydrocarbons with atomization.

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