IR thermography of flame during combustion of off-grade liquid hydrocarbons in a superheated steam jet

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Abstract. The paper represents the thermal imaging measurements of external flame during the combustion of diesel fuel and spent transmission oil in a perspective steam-atomizing burner. The experiments are conducted in a wide range of operating parameters (rate and temperature of steam and fuel consumption). A thermal imaging camera (FLIR, JADE J530SB) is used for measurements. The results show that the effective emissivity coefficient depends on the flow rate of supplied steam. The effect of the burner parameters on the temperature in the external flame of the burner is revealed. The data obtained can be used for numerical modeling of combustion.

Qualitative spraying of liquid is one of the relevant scientific and technical problems. Generation of aerosols with a small deviation in the parameters of concentration and dispersed composition is an important task in the development of various heat and power devices, coating technologies, cooling and fire extinguishing systems, and many others. For the improvement and development of modern technologies, there is a need in detailed information on the characteristics of flows obtained by spraying various substances.

One of the directions using spray nozzles is the development of efficient burners for the utilization of off-grade hydrocarbon fuels and combustible production waste. Studies conducted earlier by the scientists at the Kutateladze Institute of Thermophysics of SB RAS with the use of original autonomous vaporizing burners [1-4] showed that the combustion of such hydrocarbons was sharply intensified when a jet of superheated steam was supplied to the combustion zone. This improves the environmental characteristics of the process. However, vaporizing burners do not allow us to burn off-grade fuels due to unstable ignition, unstable and incomplete combustion of fuel.

In this work, a new burner is applied to spray liquid hydrocarbon fuel by a superheated steam jet [5]. The advantage of this promising method is that the fuel and the spraying medium (steam) are not pre-mixed with each other; steam is supplied from the nozzle in the form of a jet, along which the sprayed liquid fuel moves [6]. This fact is an important advantage, since there is no contact between the fuel and the nozzle. This prevents carbonization of surfaces and failure in the operation of the burner. To justify the effect of the parameters of a steam jet on the main characteristics of combustion of liquid hydrocarbons (composition of combustion products and specific capacity of heat release), there is a need in experimental studies of the main combustion characteristics.

For this purpose, in this work the flame of a promising burner is studied using a thermal imaging camera during the combustion of diesel fuel and spent transmission oil with fuel spraying by a
superheated steam jet in a wide range of operating parameters. This method relates to non-contact methods for obtaining information on an object, therefore it allows the temperature fields to be investigated and temperature inhomogeneities to be identified without introducing perturbations [7-12]. Also, one of the advantages of this method is spatial and temporal resolution compared to traditional methods such as the temperature measurement by thermocouples. Despite a number of advantages, the use of optical methods for studying flame results in some difficulties connected with the selection of optical characteristics of flame (emissivity and transmission coefficients) and the spectral interval and with a need to take into account the effect of the flame layer on the recording of shielded objects [13, 14].

Figure 1 shows a scheme of the burner used in the work. The main elements of the burner are as follows: a gas generation chamber; a steam atomizer connected to an external steam generator; a fuel supply pipe located near the exit of the steam atomizer; an exit nozzle. The gas generation chamber has openings for air access from the atmosphere. The steam atomizer (exit diameter is 0.5 mm) is installed vertically at the bottom of the gas generation chamber. A distinctive feature of the burner is that the fuel-supply pipe is installed at an acute angle to the horizon and does not touch the wall of the device to reduce heat losses during start of the device. In addition, a nozzle in the form of a lid with a hole in the center is installed in the upper part of the device to form a recirculation zone formed by vapors of volatile liquid fuel fractions capable of igniting and stabilizing the ignition of a steam-oil jet during operation of the device. Fuel is supplied to the fuel receiver through a fuel line. Stable fuel consumption is maintained by a fuel nozzle and a pump and controlled by electronic scales. The scheme of the process in the burner is as follows. Superheated steam is supplied to the nozzle from the steam generator to form a high-speed jet. A thin jet of liquid fuel is supplied from the fuel-supply pipe to bottom of the steam jet. Then, when the phases start interacting, this liquid fuel is sprayed to form a stable fine-dispersed gas-drop stream. In addition to dispersion, the fuel is heated and evaporated, followed by gasification and combustion of the reaction products formed in the external flame of the device.

Figure 1. Burner for combustion of liquid hydrocarbons in a superheated steam jet (dimensions: the external diameter of the burner is 60 mm, the height of the burner is 140 mm, the diameter of the nozzle is 25 mm) (a): (1) the body of the burner; (2) the steam atomizer; (3) the openings for air access; (4) the adapter of the steam generator; (5) the fuel-supply pipe; (6) a place for the supply of fuel; (7) the exit nozzle; (8) the fuel receiver; (9) flame; (10) the fine-dispersed gas-droplet flow; (11) recirculation zones of volatile fractions of liquid fuel; characteristic stable combustion mode in the burner for spent transmission oil (b).
A thermal imaging camera (FLIR, JADE J530SB) was used to measure the temperature in the high-temperature flame of the burner. This device has a high temporal resolution: frame rate is up to 177 Hz with a maximum resolution of 320x240 pixels and up to 18 kHz with a resolution of 320x4 pixels. The minimum exposure time of the frame is 6 μs. The thermal imaging camera operates in the average IR range of 2.5-5.0 μm. Powerful emission lines of flame caused by the radiation of hot combustion products (including steam, CO₂, CO) are in the same spectral range. Based on the results of previous studies [4], a narrow-band dispersion optical filter (F0616) with a bandwidth of 2.5-2.7 μm was chosen for operation. The filter was chosen due to the powerful emission lines of steam and CO₂ in this spectral interval. The temperature range of the thermal imaging camera is determined by calibrations and is 583-1773 K for the chosen filter. Data collection and primary processing of thermograms were carried out using a specialized software Altair. The thermal imaging camera was calibrated using factory calibrations for the F0616 filter with exposure time of 9, 64, 350 μs. The previous spectral analysis of the pressure and temperature of flame [4] showed the absence of expressed periodic oscillations in the flame of the vaporizing burner. To obtain the average temperature, the measurements were conducted at a frequency of 50 Hz for 1 minute. To determine the effective emissivity coefficient, similar to [15], the temperature was recorded using a platinum/platinum-rhodium B-type thermocouple (600 ... 1600°C) with a thermoelectrode diameter of 300 μm simultaneously with the control measurements performed by the thermal imaging camera (on the axis of the burner r = 0 at a height of x = 70 mm from the exit of the burner). The thermal inertia of the thermal transducer is not more than 5 s. The permitted deviations of thermo-emf from the nominal static characteristics of the transducer are ±0.005 of the measured temperature values. The time-averaged thermogram was used to determine the average temperature in the region of a junction.

It should be noted that the flame is a semitransparent optical medium, so the thermal imaging camera detects the integral radiation from all the internal layers of the medium. Using calibrations and the effective emissivity coefficient, the temperature in the observation plane is determined by the value of integral radiation obtained.

The different operation modes of the burner were experimentally studied. The relative flow rate of steam γ = \( \frac{F_v}{F_f} \) was varied in the range of 0.3 \( \div \) 0.8 (\( F_v \) is the mass flow rate of steam) and the temperature of superheated steam \( T_v \) was varied in the range of 150 \( \div \) 550°C with a constant fuel consumption \( F_f = 1 \) kg/h to provide the stable combustion of fuels in the burner.

Figures 2, 3 show the profiles of the time-average temperature in the external flame of the burner for different operation modes of the burner during the combustion of diesel fuel. Analysis of the results shows that the temperature of flame depends both on the temperature of superheated steam and the relative flow rate of steam. The different operation modes of the burner are shown in Figures 2 and 3.

**Figure 2.** Distribution of the time-average temperature \( T \) in flame along the vertical axis of the burner for different steam temperatures \( T_v \) (°C) and a constant relative flow rate of steam \( γ \) during the combustion of diesel fuel: (a) \( γ = 0.5 \); (b) \( γ = 0.8 \).
on the steam flow rate. The maximum temperature of flame reaches 1450°C (figure 2). For the relative steam flow rate \( \gamma = 0.5 \) (figure 2a), the temperature of flame increases with increasing the steam temperature. The result obtained for the case when the steam temperature was increased (in the investigated range) and \( \gamma = 0.8 \) turned out to be unexpected. The temperature of flame decreased by 100 degrees. This may be due to the fact that the increase in the steam flow rate with increasing steam temperature leads to intensification of endothermic fuel gasification reaction accompanied by the general decrease in the temperature of the reaction zone. The increase in the steam flow rate (figure 3) results in the increase in the temperature of flame, and the region with the maximum temperature shifts to the exit of the burner.

Figure 4 shows the profiles of the time-average temperature in the external flame of the burner for different operation modes of the burner during the combustion of spent transmission oil. The maximum temperature of flame reaches 1400°C that is 50°C lower than that of the diesel fuel combustion. At the same time, the effect of the steam temperature on the temperature of flame is

![Figure 3](image1.png)

**Figure 3.** Distribution of the time-average temperature \( T \) in flame along the vertical axis of the burner for different relative flow rates of steam \( \gamma \) and a constant steam temperature \( T_v \) during the combustion of diesel fuel: (a) \( T_v = 150°C \); (b) \( T_v = 250°C \).

![Figure 4](image2.png)

**Figure 4.** Distribution of the time-average temperature \( T \) in flame along the vertical axis of the burner for different combustion modes of spent transmission oil: (a) for a different steam temperature \( T_v \) (°C) and a constant relative flow rate of steam \( \gamma = 0.3 \); (b) for a different relative flow rate of steam \( \gamma \) and a constant steam temperature \( T_v = 250°C \).
The increase in the steam flow rate (figure 4b), on the contrary, leads to the decrease in the flame temperature by almost 200°C, which can be caused by a high flow rate, the temperature of which is much lower than that of the combustion products, and by the incomplete combustion of this fuel in the test burner. The obtained results of thermography are reasonably analyzed in combination of the results of calorimetry and gas analysis by analogy with [1], which is the purpose of further research.

Figure 5 shows the effective emissivity coefficient of flame in external flame as a function of the temperature of superheated steam \( T_v \) for a constant parameter \( \gamma \) (solid lines) and as a function of the parameter \( \gamma \) for a constant steam temperature \( T_v \) (dashed lines): (a) combustion of diesel fuel; (b) combustion of spent transmission oil.

The increase in the steam flow rate leads to the decrease in \( \varepsilon \) in the range from 0.43 to 0.3 (figure 5a), which may be due to an increase in the concentration of steam in the reaction zone.

**Conclusion**

The thermal imaging measurements of external flame during the combustion of diesel fuel and spent transmission oil in a perspective steam-atomizing burner were carried out. The results show that the effective emissivity coefficient depends on the flow rate of supplied steam. The effect of the burner parameters on the temperature in the external flame of the burner is revealed. The experimental data obtained can be used for analyzing the measurements of the gas composition of combustion products and heat release to scientifically validate energy-efficient and environmentally friendly methods of utilizing off-grade liquid hydrocarbons with the generation of thermal energy.

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