Flame thermography during diesel fuel combustion in the vaporizing burner

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Abstract. This paper represents a study of thermal characteristics for the flame of a liquid-fuel vaporizing burner during diesel fuel combustion in a high-temperature air jet, using the IR thermography. A thermal imaging camera FLIR (JADE J530SB) was used in the experiments. The studies carried out for different operating parameters have revealed the dependence of the effective flame emission coefficient on the air flow rate. The influence of the air flow rate on the temperature of external flame of the burner has been found. Comparison of the results was conducted for combustion in an air jet and in a jet of superheated steam.

1. Introduction
It is a well-known fact that water and steam are used in the combustion process to reduce NOx concentration [1]. They are also used in many practical applications, beginning from reducing the heat load and suppressing detonation in the combustion chamber and ending with the dispersion of heavy fuels [2] and combustion of water-fuel emulsions [3]. A number of works consider the influence of steam on combustion in gas turbine plants [4-6].

The Institute of Thermophysics of SB RAS proposed a method for combustion of liquid fuel, using superheated steam which contributes to steam gasification of carbon-containing particles during incomplete combustion of liquid hydrocarbons [7], thus maintaining stable ignition and high reaction rate. Preliminary studies carried out using different-scale autonomous burners with a power of 10-50 kW [8-10] have shown that the combustion of liquid hydrocarbons is sharply intensified when a jet of superheated steam (at a temperature of about 400 °C and a pressure of up to 1 MPa) is supplied to the combustion zone. Soot is practically absent in the final combustion products (soot content is up to 35 mg/m³) [11]. In addition, the work [10] reports that environmental specifications are significantly improved in the steam gasification mode compared with air-based technologies. The proposed method of combustion is promising for the utilization of off-grade liquid hydrocarbon fuels and combustible production waste to generate thermal energy. In the work [12] the authors use IR thermography to study the thermal characteristics for the flame of a liquid-fuel vaporizing burner during the combustion of diesel fuel in a jet of superheated steam.

For the scientific justification of the advantages of steam gasification, the combustion of diesel fuel in the air jet is studied in the paper. Using a technique similar to [12] and a thermal imaging camera, the thermal characteristics of the flame of a liquid-fuel vaporizing burner were measured. The
objective of the work is to compare the measured thermal parameters of external flame during diesel fuel combustion in an air jet and in a jet of superheated steam.

2. Experimental setup and measurement procedure

The investigations were carried out on a fire stand (Fig. 1) equipped with a new burner (10 kW), an electric heater (average power consumption is 1.5 kW), an air-supply system consisting of a reducer (maximum pressure is up to 16 bar) connected to a compressed-air supply system, an air flowmeter (measurement range of flow rate is 1-10 l/min, maximum pressure is 7 bar), an automated fuel-supply system, electronic scales to control fuel consumption, as well as necessary control and measuring devices.

![Figure 1. Scheme of the experimental setup.](image)

The main elements of the burner are as follows (Fig. 2): a cylindrical body, a combustion chamber, a steam atomizer and a gas generation chamber. The combustion chamber has openings for air access from the atmosphere. Fuel is supplied to the combustion chamber through a fuel line. Stable fuel consumption is maintained by a fuel nozzle and a pump and controlled by electronic scales. The air-supply nozzle is installed coaxially above the combustion chamber at the bottom of the gas generation chamber and is oriented vertically (exit diameter is 0.5 mm). The nozzle is connected with an external electric heater. The test burner is a vaporizing one according to the principle of operation. The scheme of the combustion process is similar to the scheme presented in [10].

The electric heater consists of three series-connected heating units. Each block is a metal pipe (external diameter is 38 mm) of 0.5 m in length with a wall thickness of 8 mm. A tubular electric U-shaped heater (maximum power is 700 W) is installed inside the pipe. The space between the heater and the pipe wall is filled with periclase (DM-1) to increase heat transfer. The wall of each pipe includes the spiral closed rectangular cross-section channels of (4×2 mm) 6 m in length (for each block). The pipes are thermally insulated outside. Temperature control sensors are mounted on the surface of each unit. The volume air flow rate was set by the air flowmeter located behind the reducer. The mass air flow rate was recalculated by the equation of ideal gas state. The air temperature was controlled by varying the power of the heaters. The gas pressure in the heater P was recorded by a digital pressure sensor. The laboratory electric heater and the air-supply system serve to obtain an airflow with parameters of flow rate of 0.1-6 kg/h and temperature of 20-600 °C.
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 320×240 pixels and up to 18 kHz with a resolution of 320×4 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 [13], 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 [13] showed the absence of expressed periodic oscillations in the flame under study. To obtain the average temperature, the measurements were conducted at a frequency of 50 Hz for 1 minute. To determine the effective emissivity coefficient ($\varepsilon$), 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 $x = 30$ mm from the exit of the burner). The thermal inertia of the thermal transducer was 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. The effective emissivity coefficient was chosen using the Altair software. The value of the effective emissivity coefficient obtained was given for the entire area.

3. Results of measurements and analysis
The measurements were conducted for a constant fuel consumption $F_f = 0.8$ kg/h to provide analogy to the operating conditions [12] and a fixed air temperature in the heater $T_{air} = 250$ °C. The mass air flow rate was set considering the equal amount of the oxidizer (air oxygen) in the present work and the oxygen of steam in [12], see Table 1. The studies were conducted for several values of the relative air flow rate $\gamma = F / F_f$, where $F$ is the mass air flow rate (or steam).
Table 1. Values of the operating parameters \( (T_{air} = T_{steam} = 250^\circ C, \ \gamma_f = 0.8 \text{ kg/h})\)

|      | air   | steam |      |      |
|------|-------|-------|------|------|
| \(\gamma\) | \(F, \text{ kg/h}\) | \(P, \text{ bar}\) | \(\gamma\) | \(F, \text{ kg/h}\) | \(P, \text{ bar}\) |
| 1.5  | 1.2   | 2     | 0.3  | 0.26 | 2     |
| 2.3  | 1.8   | 3     | 0.5  | 0.42 | 4     |
| 3.4  | 2.7   | 4     | 0.8  | 0.64 | 5     |

Figure 3 shows distributions of the time-average temperature in the external flame of the burner for a different air flow rate. 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.

\[ (a) \quad (b) \quad (c) \]

Figure 3. Thermograms of flame for different values of the relative air flow rate \( \gamma \) \((T_{air} = 250^\circ C, \ \gamma_f = 0.8 \text{ kg/h}): 1.5 \ (a); 2.3 \ (b); 3.4 \ (c). \]

The thermograms shown in Fig. 3 demonstrate a significant effect of the air flow rate on the temperature distribution in the external flame. An increase in the air flow rate leads to the increase in the flame temperature, and the area with the maximum temperature shifts to the exit of the burner, while the dimensions of the flame decrease. In the modes shown in Figs. 3a and 3b, the maximum temperature is observed at some distance from the burner exit. The fuel mixture burns out in the external flame in the diffusion mode, which indicates a lack of oxidizer in the burner tract. For \( \gamma = 3.4 \) (Fig. 3c), the dependence of the flame temperature on the longitudinal coordinate is monotonous, which indicates more complete combustion of the mixture inside the burner for the high air flow rate.

Figure 4 shows temperature distributions along the axis of the burner for different air flow rates (solid lines) and superheated steam (dashed lines). From the qualitative point of view, the profiles do not depend on the combustion mode in the jet of air or steam; in particular, the maximum temperatures are kept for the same oxygen supply. At the same time, the quantitative difference for different gasifying agents increases with increasing consumption. Higher values of the maximum temperature (the difference exceeds 200 °C at \( \gamma = 0.8 \) with steam and \( \gamma = 3.4 \) with air) and a long length of the flame are typical for combustion modes with steam gasification. The latter can be explained by the...
fact that steam in the modes with $\gamma = 0.8$, $0.5$ is supplied at a higher pressure than air at $\gamma = 3.4$, $2.3$ (see Table 1). As a consequence, the speed of the steam jet is higher than that of air, which contributes to the elongation of the flame. At equal pressure in the modes at $\gamma = 1.5$ with air and $\gamma = 0.3$ with steam, flames have approximately the same length. The higher temperature of the flame in the case when steam is used may be due to the fact that the mass flow rate of steam is approximately five times lower than the air flow rate. Considering their equal temperature which is much lower than the temperature of combustion products, it can be concluded that a significant amount of nitrogen supplied with air leads to a decrease in the flame temperature (as well as a possible increase in the formation of nitrogen oxides).

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\begin{array}{c|c|c}
\gamma & \text{air} & \text{steam} \\
1.5 & 0.62 & 0.3 \\
2.3 & 0.59 & 0.5 \\
3.4 & 0.54 & 0.8 \\
\end{array}
\]

Table 2. Values of the effective emissivity coefficient and maximum temperature in the external flame for the modes under study ($T_{\text{air}} = T_{\text{steam}} = 250^\circ\text{C}$, $F_j = 0.8$ kg/h)

The studies conducted allowed us to obtain data on thermal characteristics of flame during the combustion of diesel fuel in a vaporizing burner with the supply of a jet of air to the combustion zone. The temperature distributions and effective emissivity coefficient of flame as a function of the mass flow rate of air were obtained. The measurements were compared with the data obtained earlier [12].
for the combustion mode in a jet of superheated steam. New results can be used for the scientific justification of energy-efficient and environmentally safe methods of utilizing off-grade liquid hydrocarbons with the generation of thermal energy.

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