IR diagnostics of a flame of a new burner when burning liquid hydrocarbons in a steam jet

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Abstract. In the present work, we performed IR diagnostics in the external flame of a new burner using the example of waste engine oil being sprayed by a high-speed jet of superheated steam. The experiments were carried out in a wide range of operating parameters (steam flow rate and temperature and fuel flow rate). In measurements, we used a FLIR thermal imaging camera of the special JADE J530SB series and platinum-rhodium-platinum-rhodium thermocouple of type B. Instantaneous and average temperature fields are obtained. The influence of device operation parameters on the temperature in the external flame of the burner is established. The maximum temperature reaches 1240°C. With increasing mass concentration of steam, a decrease in temperature is observed. This is due to dilution of a combustible mixture and a decrease in its heat capacity. A decrease in the flame temperature in the presence of steam may indicate a decrease in formation of thermal nitrogen oxides.

1. Introduction

Disposal of substandard liquid hydrocarbons is one of the urgent environmental problems. Burning is the most common way of their utilization to produce thermal energy. The use of traditional methods of burning liquid fuel applying spray nozzles for the disposal of liquid combustible waste is not effective. There are problems of coking and clogging of the fuel supply channels, combustion instability, increased soot formation and low completeness of fuel burnout.

One of the effective methods for spraying liquid hydrocarbons is the technology of burning fuel at its interaction with a high-speed jet of superheated steam [1]. Due to this, a finely dispersed gas-droplet flow is generated, which positively affects the quality of fuel combustion. At that, the use of superheated steam provides a number of advantages as compared to air; in particular, the concentration of nitrogen oxides in the combustion products is reduced [1]. This is associated with a decrease in the temperature and propagation velocity of the flame [2–4] due to an increase in the heat capacity of the combustible mixture in the presence of steam. In addition, the presence of steam can affect chemical reactions during combustion [5–6]. Water at high temperature promotes the formation of additional OH radicals [7–8], which are actively involved in the oxidation of both soot particles [9] and carbon monoxide [10].

Based on the proposed method for spraying liquid fuel, a burner with an enlarged combustion chamber and tangentially located outlet nozzle has been developed. This design allows improvement in the quality of burning substandard fuel by increasing the residence time in the combustion chamber. One of the important parameters of the combustion process is the flame temperature. In this work,
experimental studies on the influence of operating parameters on the temperature in the external flame of the burner have been carried out.

2. Experimental setup and methods
The thermocouple is the most common device for measuring flame temperature. However, it has several features: the device can only measure local, time-averaged temperature values, which in many cases is not enough for understanding individual processes. In [11], the use of infrared cameras is proposed to expand the spatial and temporal range of measurements. Such processes as the destruction of material under the influence of temperature [12-15], determination of jet fire radiation [17-18], pool fire radiation [19-20], thermal radiation of fire whirl [21], fireballs [22], determination of the rate of fuel droplet evaporation [23] and etc. can be studied by those cameras (thermal imagers). It should be noted that the infrared thermographic camera registers radiation from the object. Depending on the type of camera, the readings are converted to the temperature values, while either a known or measured experimentally emissivity is used to convert the signal [19]. One of the methods to obtain the value of this parameter is temperature measurement at a flame point using any contact method, for example, a thermocouple [19]. The obtained value is usually taken as a constant over the entire flame surface. When measuring the temperature at the same point with a thermal imager, such values of emissivity are selected that the temperature readings produced by the thermal imager coincide with the measurement of the thermocouple. In addition, for the correct calculation of temperature, the following parameters should be taken into account: the distance between the camera and the measured object, the ambient temperature, and relative humidity, since they are all connected with the transmission of radiation through the medium, which separates the radiating object and the measuring equipment (IR camera) [21, 24].

2.1. Burner
To perform experimental studies, the authors proposed a new design of the burner with an increased volume of the combustion chamber and a tangentially located outlet nozzle in which liquid fuel is sprayed by a high-speed jet of superheated steam (Figure 1).

![Figure 1. Photograph and scheme of a new burner.](image-url)
cylindrical body near the left cover, there are tangentially directed holes for additional natural airflow from the environment into the gas generation chamber. The output nozzle is mounted tangentially on a cylindrical body near the right cover and is oriented vertically upwards to ensure the possibility of measurements using a flow calorimeter. The inner diameter of the outlet nozzle is 50 mm. The total dimensions of the burner are as follows: external diameter of the combustion chamber is 800 mm, length is 250 mm, and height is 180 mm. All elements of the burner are made of stainless steel of grade 12X18H10T.

2.2. Experimental setup and measurement methods
The thermal characteristics of the flame at waste oil combustion in a new burner were studied in an experimental setup (Figure 2). The setup consists of: burner; water supply system (flow rate $F_v = 0.2 \div 1.4$ kg/h); electric steam generator (degree of steam superheating $T_s$ up to 400 degrees); system for air supply instead of steam (flow rate $F_a = 0.3 \div 1.0$ kg/h); and system for liquid fuel supply and heating (fuel flow rate $F_f = 0.4 \div 2.2$ kg/h). An experimental setup for studying the soot-steam regime of liquid hydrocarbon combustion is part of the unique scientific facility “Large-scale thermo-hydrodynamic test-bench for studying the thermal and gas-dynamic characteristics of power plants” [25].

To measure the temperature in the flame, a FLIR thermal imaging camera of a special JADE J530SB series was used (the frame frequency up to 177 Hz with a maximum resolution of 320x240 pixels and up to 18 kHz with a resolution of 320x4 pixels). To start and achieve stable operation of the device, the research methodology, similar to that of [26], was used: a narrow-band dispersive optical filter F0616 with a passband of 2.5–2.7 μm was chosen for operation; the measurements were carried out at a frequency of 60 Hz for 20 sec with a frame size of 320x240 pixels (scale factor 1.4mm per pixel); to determine the effective emissivity, simultaneously with measurements by a thermal imager at control points (on the axis of the burner $r = 0$, at height $x = 70$ mm from the burner edge), the temperature was recorded using a platinum-rhodium-platinum-rhodium thermocouple of type B (wire diameter of 300 μm). When making measurements with a thermal imaging camera, it is also necessary to take into account that the flame is a semitransparent three-dimensional optical medium. Therefore, the thermal imager registers integral radiation from all internal layers of the medium from the value of which the temperature in the observation plane is determined using the calibrations of thermocouples and the effective emissivity.

![Figure 2](image-url) A photograph of experiments setup with IR camera.

3. Results
The measurements used waste engine oil (density of 863.25 kg/m³, viscosity of 41.8 mm²/s, higher heat of combustion of 45.3 MJ/kg, C of 85.6%, H of 13.2%, S of 0.6% (by weight)). The oil was preheated to a temperature of 50°C, which made it possible to lower its viscosity.

In [29], for this design of the burner, the results of preliminary measurements of the gas composition during waste engine oil combustion were obtained and regimes with the minimum values of carbon monoxide in equilibrium combustion products (CO <10 ppm) were found, which were selected for investigation in the current work. Typical photos of the flame in these regimes are shown in Figure 3.
Such a choice of regimes is explained by the fact that at minimum values of carbon oxides high completeness of fuel combustion is usually achieved.

Figure 3. Photographs of the burner flame at different steam concentrations in the regimes with minimal CO content (nozzle diameter of 50 mm).

The characteristic thermograms of the burner flame are presented in Figure 4. The field of instantaneous temperature shows the essentially turbulent regime of flame combustion. The performed frequency analysis did not reveal any periodic dependence of temperature fluctuations of the flame on the parameters of steam and fuel. The isotherms of the average temperature field are conical in shape, which is characteristic of diffusion combustion. This means that at the burner outlet, the flow contains unreacted components that burn out as ambient air enters.

Figure 4. Characteristic temperature fields in the flame (Re ~45000): instantaneous (a), average (b).

It is shown in [1] that the temperature of superheated steam weakly affects the main indicators of fuel combustion, including the external flame temperature. This is caused by the fact that the temperature in the combustion chamber is significantly higher than the steam temperature and due to convective and radiant, heat transfer the temperature in the zone of steam mixing with the products of thermal decomposition and incomplete fuel combustion reaches approximately the same value for different initial steam temperatures. The same dependences have been established for the studied spray burner.

The dependences of flame temperature on steam and fuel flow rate are shown in Figure 5. The temperature profiles have the same shape, independent of the flow of steam or fuel flow in the considered range of regimes. An exception is a regime that corresponds to the region of a high content of CO > 500 ppm (Figure 5-b): the temperature profile has a maximum at a certain distance from the nozzle, which
indicates fuel underburning in the combustion chamber. The maximum temperature reaches 1240°C. With an increasing mass concentration of steam, a decrease in temperature is observed. This is due to the dilution of the combustible mixture and a decrease in its heat capacity. A decrease in the flame temperature in the presence of steam may indicate a decrease in the formation of thermal nitrogen oxides.

![Figure 5](image)

**Figure 5.** Profiles of average temperature in the flame along the vertical axis of the burner (steam temperature of 260°C): (a) at different flow rates of superheated steam, kg/h (fuel flow rate of 1 kg/h); (b) at different fuel flow rates, kg/h (steam flow rate of 0.8 kg/h).

**Conclusions**
Using thermal imaging and thermocouple measurements, temperature distributions in the flame of a new burner were obtained when spraying liquid fuel by a steam jet. The instantaneous temperature field shows the essentially turbulent regime of flame combustion. The isotherms of the average temperature field are conical in shape, which is characteristic of diffusion combustion. A dependence of the flame temperature on the steam temperature is not detected. This is caused by the fact that the temperature in the combustion chamber is significantly higher than the steam temperature and due to convective and radiant heat transfer, the temperature in the zone of steam mixing with the products of thermal decomposition and incomplete combustion of fuel reaches approximately the same value for different initial steam temperatures. The maximum flame temperature reaches 1240°C. With an increasing mass concentration of steam, a decrease in flame temperature is observed. This is due to the dilution of the combustible mixture and a decrease in its heat capacity. A decrease in the flame temperature in the presence of steam may indicate a decrease in the formation of thermal nitrogen oxides.

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