Combustion of kerosene sprayed with a jet of superheated steam

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Abstract. In the present work, the effect of forced air supply on the combustion process of liquid hydrocarbons was studied using diesel fuel as an example. The content of the flame intermediate components and temperature distribution along the flame symmetry axis were studied using an atmospheric burner in which liquid fuel is atomized by a steam jet. The gas composition of equilibrium combustion products and heat release were also investigated. The influence of the excess air ratio in the combustion chamber of the burner device on the thermal and environmental characteristics was shown.

1. Introduction

Transportation, industry, and heating systems consume large amounts of fossil fuels, resulting in high emissions of various pollutants, including nitrogen oxides, carbon monoxide, unburned hydrocarbons, and particulate matter. Therefore, an important task is to improve the characteristics of fuel combustion, including the reduction of harmful emissions.

There is also a trend towards the development of local sources of heat and energy, such as micro-gas turbines, which have high efficiency in generating electricity for the efficient use of generating capacity of the power grid [1]. A micro-gas turbine system can generate electricity and heat (steam or hot water) simultaneously, and can be used in remote locations that have a need for electricity and heat, including these needs in emergency situations. At that, such devices can operate on liquid fuel, which is easy to transport if it is necessary to place equipment in hard-to-reach places. Therefore, the development of low-emission burners with low NOX emissions, which can be used in these areas, including through the injection of superheated steam, is relevant [2].

The world scientific literature notes that water and steam in combustion chambers can be used in practice to solve a number of problems: from reducing the heat load and suppressing detonation [3] in the combustion chamber to dispersing heavy fuels and burning water-fuel emulsions. Water injection is also used to reduce effectively NOx emissions. A decrease in NOx emissions is usually associated with an increase in the heat capacity of mixture during combustion of fuels (physical effect): hydrogen-air [4] mixture, combustion of methane-air mixture [5–7], and propane-butane mixture [8]. At the same time, it is noted in some papers [9,10] that the addition of steam leads not only to dilution of the combustible mixture (physical effect), but it also changes the process of some elementary reactions (chemical effect). It is noted in [11] that the use of steam injection technology is more efficient than the use of recirculation gas technology in the presence of steam.

The combustion processes of substandard liquid hydrocarbon fuels and industrial waste with the supply of a jet of superheated steam to the combustion zone were studied during combustion of diesel fuel and waste engine oil in developed promising direct-flow burners in [12–16]. The authors note that
the use of superheated steam allows reduction in the content of nitrogen oxides in exhaust gases by up to 30% with high combustion efficiency of low-grade fuel. In this work, this effect is associated with a decrease in the flame temperature, providing reduction in formation of “thermal” NOx. The steam gasification process maintains a high combustion efficiency. The authors note that this combustion method is one of the most promising ways to utilize low-grade fuels and industrial waste that can be incinerated (waste oils, etc.).

However, the kinetics of combustion of liquid hydrocarbons, especially substandard ones, during steam injection is still poorly understood, the exact mechanisms have not yet been discovered, which does not allow reliable numerical calculations when designing burners. Therefore, in the framework of this work, to obtain new results and dependences that supplement information on the combustion mechanisms in the presence of steam, the maps of the burner operating regimes during the combustion of Jet A-1 fuel have been investigated. For the selected parameters of steam supply, the flame temperature was measured. The study was carried out in a spray type burner, which was investigated by the authors in [2,16] when burning diesel fuel.

2. Experimental setup and methods
The burner, whose operation was described in detail in [2,16], is used in the current study (see figure 1).

![Figure 1. Combustion of kerosene in a spray burner.](image-url)

We should note that the burner power is in the range of 5-20 kW. A feature of this burner is that due to steam gasification of fuel in a high-velocity jet, a highly dispersed two-phase flow, intense ignition and complete burnout of fuel with low production of toxic products are obtained. The supply of steam to the combustion zone provides steam gasification of the products of thermal decomposition and incomplete combustion of fuel with formation of water gas (CO + H2), increasing the degree of carbon burnout. Liquid fuel is sprayed by a high-velocity jet of superheated steam without the use of fuel injectors, which ensures formation of a fine-dispersed flow with separate supply of fuel and oxidizer to the combustion chamber. This spraying method prevents clogging of fuel channels and spraying devices and burns liquid hydrocarbons effectively. At the same time, steam promotes
decomposition of complex organic compounds and hydrocarbons, accelerating the processes of evaporation and combustion. By supplying steam to the combustion zone, the flame temperature can be reduced, which can help reduce emissions of nitrogen oxides.

Kerosene combustion in a burner with a jet of superheated steam was studied with the help of an experimental setup used in [17]. The setup consists of: burner; water supply system (flow rate \( F_v = 0.2 \div 1.4 \text{ kg/h} \)); electric steam generator (steam overheating degree \( T_s \) of up to 400 degrees); air supply system, instead of steam (flow rate \( F_{air} = 0.3 \div 1.2 \text{ kg/h} \)); system for liquid fuel supply and heating (fuel flow rate \( F_f = 0.4 \div 2.2 \text{ kg/h} \)) (see figure 2). The experimental setup for studying the soot-steam combustion of liquid hydrocarbons is part of the unique research facility USU “Large-scale thermo-hydrodynamic setup for studying the thermal and gas-dynamic characteristics of power plants” [18].

![Figure 2. Scheme of experimental setup: 1 – burner, 2 – electric steam generator, 3 – water tank, 4 – plunger dozing water pump, 5 – manometer, 6 – steam temperature sensor, 7 – electronic scales for fuel mass control, 8 – fuel tank, 9 – fuel heating system, 10 – fuel filtration system, 11 – fuel pump, 12 – dozing electromagnetic valve, 13 – automated control unit.](image)

To plot a regime map of burner operation during the combustion of kerosene sprayed with superheated steam, a flow-through calorimeter with installed Testo 350 gas analytical equipment was used [17]. To study the flame temperature in the selected regimes, we used a platinum-rhodium-platinum-rhodium thermocouple of type B (wire diameter of 0.3 mm) mounted on a coordinate-moving device to determine the average flame temperature along the flame symmetry axis.

3. Results
The mapping of burner operating regimes during Jet A-1 fuel combustion was carried out: at a steam flow rate \( F_v \) in the range of 0.4-1.2 kg/h and fuel flow rate \( F_f \) in the range of 0.4-1.8 kg/h (deviations during adjustment from the specified average flow rates are within ±5% for steam and ±2.5% for fuel). The characteristics of the fuel used are shown in Table 1.

| Properties                        | Values  |
|-----------------------------------|---------|
| Density at 20°C (kg/m³)           | 788.89  |
| Viscosity at 24.1°C (mm²/s)       | 1.1     |
It was previously established [16] that the temperature of superheated steam has little effect on the main characteristics of liquid fuel combustion; therefore, the measurements were carried out at a constant steam temperature $T_s = (260\pm10)^\circ C$, which provides sufficient steam superheating for the reaction and minimum energy consumption for steam superheating, simultaneously. Also, for comparative analysis, the heated compressed air with $F_{air}$ in the range of 0.4 – 1.2 kg/h was supplied instead of a jet of superheated steam. The air was heated to temperature $T_a = (260\pm10)^\circ C$.

The regime map of carbon monoxide content in the combustion products at a supply of a jet of superheated steam jet (figure 3-a) and heated air instead (figure 3-b) is shown in figure 8. The values of carbon monoxide in figure 3 are given in grams of matter per kilogram of fuel burned. Conversion from volumetric values [ppm], obtained using gas analytical equipment, into relative mass values was carried out according to the method specified in [19]. The red zone in the figure corresponds to regimes that do not meet any environmental class in terms of carbon monoxide content in combustion products according to standard EN: 267.

![Figure 3. Regime maps of CO content in equilibrium combustion products with the supply of (a) superheated steam and (b) heated air.](image)

Based on the obtained operating maps, several regimes with different power of the burner, characterized by low readings for the CO content in flue gases, were selected: $F_f = 1.30, 1.36, 1.41$ kg/h, at $F_v = 0.4, 0.6, 0.8$ kg/h and $F_{air} = 0.51, 0.76, 1.03$ kg/h, respectively. We also measured a regime with a high flow rate of superheated steam at $F_f = 1.54$ kg/h and $F_v = 1.2$ kg/h. The flow rates during the supply of a heated air jet were calculated based on the correspondence of the intensity of the dynamic effect of a gas jet on a drop of fuel $Y_{jet}$ to the regimes with the supply of superheated steam given in [20].

For the selected parameters of steam supply, the profiles of the average temperature along the axis of flame symmetry were obtained (figure 4). It can be seen that when burning kerosene in the regimes with low CO contents in exhaust gases with the supply of superheated steam or air, instead of it, the maximum temperature is reached at a certain distance from the flame base, which indicates fuel
afterburning when external air enters. With an increase in the steam or air flow rate, the position of the maximum temperature shifts closer to the flame base, while for air an increase in temperature is observed. With an increase in the flow rate of superheated steam, a slight increase in temperature is observed, and for the regime with increased steam content in the combustible mixture, a significant decrease in temperature is observed. A decrease in flame temperature in the presence of steam may indicate a decrease in formation of thermal nitrogen oxides in the combustion products. Also, when kerosene is burned with air, the maximum temperature in the flame turns out to be slightly higher than the maximum temperature with steam (> 50°C).

![Profiles of average flame temperature along the vertical axis of the burner nozzle with the supply of (a) superheated steam and (b) heated air.](image)

**Figure 4.** Profiles of average flame temperature along the vertical axis of the burner nozzle with the supply of (a) superheated steam and (b) heated air.

**Conclusion**

The process of combustion of liquid hydrocarbons sprayed with a jet of superheated steam has been experimentally studied using Jet A-1 fuel as an example. The studies were carried out using a laboratory sample of a burner (with a power of up to 20 kW), which implements a method of liquid fuel spraying when interacting with a high-velocity jet of superheated steam.

The influence of operating parameters on characteristics of the combustion process in the presence of superheated steam was studied: the maps of burner operating regimes were plotted, and the flame temperature was measured for the selected parameters of steam supply.

Characteristics of the process are compared when fuel is sprayed with a steam jet and an air jet instead. The flow rates during the supply of a heated air jet were calculated based on the correspondence of the intensity of the dynamic effect of a gas jet on a drop of fuel to the regimes with the supply of superheated steam. It was found that when kerosene is burned being sprayed with superheated steam, lower flame temperatures are achieved as compared to air at low CO concentrations, which can affect the reduction of formation of thermal nitrogen oxides in combustion products.

The results obtained can be used for mathematical modeling when developing liquid fuel burners that ensure high efficiency of fuel combustion at low values of harmful substance emissions.

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