Combustion of liquid hydrocarbons in a jet of superheated steam

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Abstract. The process of combustion of liquid hydrocarbons with spraying by a jet of superheated steam in a direct-flow burner is studied experimentally in this work at the example of diesel fuel. The aim of research is to study the effect of regime parameters (steam and fuel flow rate) on the main characteristics of the process. Specific amount of heat and useful thermal power were determined from the measurements on a flow calorimeter, a gas analyzer Testo 350 was used to perform the gas analysis of combustion products. A regime map was plotted and results of characteristic combustion conditions were presented. The regimes of high completeness of fuel combustion with low production of toxic combustion products were determined.

1. Introduction
The method of combustion of liquid hydrocarbon fuel in a flow of superheated steam with gasification of carbonaceous particles of incomplete combustion of liquid hydrocarbons is proposed at IT SB RAS [1]. It was shown using the burners of evaporation type [2] that the supply of superheated steam to the zone of combustion of liquid hydrocarbons intensifies combustion dramatically. This method of combustion is characterized by stable ignition, high completeness of fuel combustion, efficiency, possibility of recycling substandard liquid hydrocarbons and combustible waste with obtaining the thermal energy.

The next important step in the search for the methods of intensifying the combustion of liquid fuels is the original method proposed by the authors for creating a two-phase flow, consisting of finely dispersed droplets of fuel and superheated steam as a carrier phase, in a burner [3]. The specific feature is that in contrast to the traditional fuel nozzles [4,5], liquid fuel is sprayed directly by a high-speed steam jet not using a fuel injector. In practice, this is an important advantage, since there is no contact of liquid fuel with the nozzle, and this prevents coking of its surfaces and subsequent failures in burner operation.

To find the optimal regime parameters (such as steam flow rate and temperature, and fuel flow rate), which ensure high completeness of fuel combustion and low concentrations of toxic combustion products, the process of diesel fuel combustion is experimentally investigated in this paper when it is sprayed by a jet of superheated steam in a direct-flow burner.
Burner devices operating on this principle can be designed for different capacities and used to equip boilers, including when solving problems of autonomous heat supply to industrial and residential facilities.

2. Experimental setups and measurement methods

2.1. Experimental apparatus

The scheme of the burner is shown in Figure 1-a; the main components are as follows: a body, together with the outlet nozzle it forms a gas generation chamber; base; steam nozzle (diameter of 0.5 mm); fuel line. The fuel supply tube is installed at an acute angle to the horizon; the end of the tube is located near the steam jet base and has a bevel. A stable mass fuel flow rate is set by the fuel nozzle and pump; the mass is controlled by means of electronic scales. Water heating and steam superheating are carried out by an electric steam generator [3]. The design provides a natural air flow from the atmosphere into the reaction zone through the holes in the lower part of the body (Figure 1-a). Atmospheric air is required for ignition of liquid fuel.

![Figure 1](image)

**Figure 1.** (a) Scheme of experimental burner; (b) visualization of diesel fuel spraying by a jet of superheated steam

The following scheme for dispersing and combustion of liquid fuel is implemented in the burner (Figure 1-a). Steam flows from the nozzle in the form of a jet, when liquid fuel flows on this jet, a fine-dispersed gas-droplet flow is formed (Figure 1-b). In addition to spraying the fuel, superheated steam raises the temperature of fuel droplets, and this intensifies mass transfer and mixture formation, contributing to sustained ignition. The ignition of dispersed fuel at the beginning of the process is carried out by an external gas burner through the air supply openings in the lower part of the body. Due to the jet flow onto the inner plane of the nozzle, a recirculation region is formed in the peripheral zone (Figure 1-a); in this region ignition is initiated at start-up and ignition of the steam-oil jet is stabilized during operation of the device. At that, steam gasification of the products of thermal decomposition of fuel occurs in the combustion zone, and this increases the combustion characteristics of liquid hydrocarbons. The resulting combustible mixture of CO and H₂ burns in a flame, mixing with oxygen from the outer atmosphere.

2.2. Experimental methods
To analyze the efficiency of the studied method of dispersion and combustion of liquid fuels, the main characteristics of the combustion process were measured in this work: heat release and composition of combustion products.

The useful thermal power $W$ at combustion of diesel fuel with spraying by a jet of superheated steam was determined by the measurements on a flow calorimeter [2] under the steady state operation of device as the difference between the thermal energy received by the working body from the reaction products and energy spent for maintaining the process (per a unit of time). The specific amount of heat ($q$) was determined under the stationary experimental conditions by the difference in the temperature of the coolant (water) at the inlet and outlet and by the flow rate of coolant and fuel.

To control the composition of gaseous combustion products, the TESTO 350 gas analyzer was used. It allows the measurement of the following components: $O_2$ – 0 ... + 25% vol., $CO$ – 0 ... 500 ppm, $NO$ – 0 ... + 300 ppm, $NO_2$ – 0 ... + 500 ppm, $SO_2$ – 0 ... + 5,000 ppm, $CO_2$ – 0 ... + 50% vol. Sampling of reaction products was carried out at the calorimeter outlet.

The experiments were carried out under the following conditions: steam flow rate $F_s$ in the range of 0.2-1.4 kg/h and fuel flow rate $F_f$ in the range of 0.4-2.2 kg/h. At that, the relative mass flow rate of steam $\gamma = F_s/F_f$ varied from 0.2 to 1.0. The range of $F_s$ values corresponds to the working range of the dosing water pump and productivity of the laboratory steam generator required for steam superheating up to the set temperature ($T_s$=250°C). The limits of fuel flow rate $F_f$ correspond to the permissible power of burner in the laboratory measurements. The temperature of superheated steam in experiments was set constant $T_s=(250\pm10)$°C because it was previously determined that further increase in the degree of steam superheating ($> 250$°C) does not affect the combustion of fuel. The steam pressure as a function of $F$ and $T_s$ values was $P = 4.8\pm11$ bar, steam superheating $T_s-T_b$ was 100°C ($T_b$ is the temperature of saturated steam).

3. Results and discussion

Data on heat generation and composition of cooled combustion products were obtained at diesel fuel combustion with spraying by a jet of superheated steam in a direct-flow burner. The map of CO concentrations and photographs of characteristic regimes are presented in Fig. 2. The boundaries of the flame blowout area are plotted by the results of visual observations; they depend on the ratio of fuel and oxidizer in the mixture. In a region with a low CO content (<50 ppm), the burner flame has a pronounced blue color, characteristic of the combustion of gases, in particular, hydrogen. This is due to emission of OH radicals formed in the reaction zone at steam gasification of liquid fuel. In a region with an increased CO content, in equilibrium combustion products (> 500 ppm), the outer flame takes bright yellow color with orange "tongues"; this is caused by the glow of incandescent soot particles and indicates incomplete combustion of fuel at high flow rates. This feature is associated with geometric characteristics of the burner (its dimensions, shape of the combustion chamber, etc.) and, consequently, limitations of the maximal power. In the region close to burning blowout, instability of fuel ignition is observed, which is also characterized by a high content of CO in the combustion products.

The results of calorimetric measurements and gas analysis, performed under the characteristic regimes indicated by the symbols in Figure 2, are presented in Table 1. Investigation results show that maximal specific amount of heat $q$ is achieved under the conditions of low CO content in the combustion products. In the regimes with high CO content (> 500 ppm), the completeness of fuel combustion is low (regimes No.5, 10 in Table 1), and this is consistent with visual observations (Figure 2). The maximal power of the burner is about 20 kW. The NOx content in the studied regimes is below the maximum allowable concentration, it does not exceed 60 ppm.
Figure 2. Map of CO concentrations (ppm) in equilibrium combustion products at $T_s=(250\pm10)\degree C$; $\leftrightarrow\leftrightarrow$ – regimes considered by the current research.

Table 1. Results of calorimetric measurements and gas analysis at $T_s=(250\pm10)\degree C$

| No. | $F_v$, kg/h | $F_f$, kg/h | $P$, bar | $q$, MJ/kg | $W$, kW | CO ppm | CO $\text{gram per 1 fuel kg}$ | NO$_x$ ppm | NO$_x$ $\text{gram per 1 fuel kg}$ | CO$_2$ % | CO$_2$ $\text{gram per 1 fuel kg}$ |
|-----|-------------|-------------|---------|----------|--------|-------|-------------------------------|-----------|-------------------------------|--------|-------------------------------|
| 1   | 0.48        | 0.69        | 4.8     | 43.4     | 8.3    | 132   | 1.83                          | 23        | 0.66                          | 9.0    | 3043                          |
| 2   | 0.6         | 0.86        | 5.8     | 43.7     | 10.4   | 56    | 0.68                          | 30        | 0.66                          | 10.1   | 3028                          |
| 3   | 0.8         | 1.15        | 7.8     | 43.1     | 13.7   | 20    | 0.20                          | 41        | 0.71                          | 12.5   | 3090                          |
| 4   | 1.0         | 1.43        | 9.9     | 43.5     | 17.3   | 6     | 0.05                          | 39        | 0.57                          | 14.4   | 3074                          |
| 5   | 1.1         | 1.57        | 9.7     | 38.4     | 18.5   | Out of measurement range (CO > 500 ppm) |                                      |                                      |                                      |        |                               |
| 6   | 0.6         | 1.0         | 5.8     | 43.3     | 12.0   | 33    | 0.33                          | 44        | 0.79                          | 12.1   | 3018                          |
| 7   | 0.8         | 1.0         | 7.7     | 42.4     | 11.8   | 39    | 0.48                          | 26        | 0.58                          | 10.2   | 3019                          |
| 8   | 0.8         | 1.2         | 7.8     | 43.6     | 14.5   | 12    | 0.12                          | 46        | 0.74                          | 13.2   | 3092                          |
| 9   | 0.8         | 1.4         | 7.8     | 43.8     | 17.1   | 36    | 0.29                          | 56        | 0.76                          | 15.8   | 3112                          |
| 10  | 0.8         | 1.6         | 7.8     | 38.2     | 17.0   | Out of measurement range (CO > 500 ppm) |                                      |                                      |                                      |        |                               |
| 11  | 1.2         | 1.4         | 10.2    | 42.6     | 16.6   | 6     | 0.06                          | 36        | 0.56                          | 13.7   | 3064                          |
| 12  | 1.2         | 1.6         | 9.6     | 42.8     | 19.0   | 10    | 0.08                          | 43        | 0.58                          | 15.8   | 3065                          |
| 13  | 1.4         | 1.6         | 11.0    | 42.9     | 19.1   | 28    | 0.22                          | 43        | 0.58                          | 15.7   | 3066                          |

$F_v$ – steam mass flow rate, $F_f$ – mass fuel consumption, $P$ – steam pressure, $q$ – specific amount of heat, $W$ – useful thermal power.

4. Conclusion
Experiments on measuring heat release and composition of cooled combustion products at diesel fuel combustion with spraying by a jet of superheated steam have been carried out in a direct-flow burner under various operating conditions. A regime map was plotted and results of characteristic combustion regimes were presented. A correlation between CO concentration in equilibrium combustion products...
and specific heat release was made. The regimes with high completeness of fuel combustion at low production of toxic combustion products were determined. The experimental data obtained at an example of diesel fuel allow one to organize the optimal operation regimes of the studied burner and confirm the prospects of the offered method for dispersion and combustion of liquid hydrocarbons in a jet of superheated steam.

The results obtained are in demand for the scientific substantiation of energy efficient and environmentally friendly ways of utilizing substandard liquid hydrocarbons with heat production, as well as verification of the mathematical model and numerical simulation of the process.

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