The study of the effect of forced air supply on the combustion of liquid fuel dispersed by 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 intermediate components of the flame and the temperature distribution along the flame symmetry axis were studied using an atmospheric burner with liquid fuel atomizing by a steam jet. The gas composition of equilibrium combustion products and the heat release were 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

Industry, transportation sectors, and heating systems consume large amounts of fossil fuels, resulting in a high level of emissions of various pollutants, including nitrogen oxides, carbon monoxide, unburned hydrocarbons, and solid particles. Therefore, an important goal is to improve fuel combustion characteristics, including the reduction of harmful emissions.

One of the ways to improve the efficiency of fuel combustion and environmental performance is the addition of water or steam in the combustion systems [1–3] and the use of water-fuel emulsions [4, 5]. A study of the fuel combustion patterns is required to understand the occurring processes. Different parameters of steam or water injection, such as the speed and location of the supply, flow rate, and temperature of the injected substance can affect the characteristics of fuel combustion.

For instance, direct injection of water into the combustion chamber can reduce NOx emissions by up to 61%, as well as significantly improve the operating parameters of the diesel engine [1]. The results of an evaluation of various schemes of steam injection in the diesel engine have shown that steam injection into the cylinder and at the inlet of the turbine can reduce fuel consumption [2].

The authors have designed a new atmospheric burner for the combustion of liquid hydrocarbons [6]. In this device, fuel is atomized by a jet of superheated steam, which provides efficient combustion of liquid combustible waste products, avoiding clogging and coking of nozzles. At the same time, the presence of steam in the combustion zone decreases the flame temperature, which prevents the formation of NOx [7]. The performed studies of thermophysical and environmental characteristics have shown the effectiveness of this combustion method [6]. However, the burner device designed for laboratory studies is not complete. For its specific practical applications, for example, in boiler technology, modification is required. One of its drawbacks is uncontrolled air supply to the combustion zone. This prevents the control of mode parameters and combustion characteristics. Therefore, the next step of our research is a controlled forced air supply to the burner.

The purpose of this work is to study the combustion characteristics of liquid hydrocarbons dispersed by a superheated steam jet at a controlled excess air ratio in the combustion chamber. The novelty of the
work is in the study of a new method of liquid fuel dispersion, testing a new burner device and the results, which supplement the information about the mechanisms of combustion in the presence of steam.

2. Burner device
A new atmospheric atomizing burner with the injection of superheated steam into the combustion zone (Fig. 1) is investigated in the work. The burner capacity is 10 kW. In such a device, the method of dispersion and combustion with steam gasification of products of thermal decomposition and incomplete combustion of liquid fuel is realized [8]. The dimensions of the burner (Fig.1-b) are: external diameter of the burner of 60 mm, height of 140 mm, and the diameter of the outlet hole of 25 mm. Steam nozzle (full jet angle of 20°) is installed coaxially with the base of the gas generation chamber and directed vertically upwards. The fuel supply pipe is placed at an angle to the horizon, and the end of the pipe is close to the base of the steam jet and has a bevel (Fig.1-b). There is also a forced air supply to the combustion chamber through an annular manifold located outside in the lower section of the burner. Uniform distribution of air into the combustion chamber is carried out through 18 holes (Ø 4 mm) made in the burner body. The air manifold is a distinctive feature of the new design of the burner in comparison with the existing one [6].

![Burner device: (a) photograph of the burner; (b) the scheme.](image)

Figure 1. Burner device: (a) photograph of the burner; (b) the scheme.

The burner device functions as follows (Fig.1-b). Superheated steam is supplied to the burner device from the steam generator through the steam nozzle mounted in the base of the burner. The high-speed jet of steam flows from the nozzle into the gas generation chamber and heats the elements of the burner device. Liquid fuel with a given flow rate is fed to the base of the steam jet in the form of a thin jet through the fuel supply tube. As a result of the interaction of gas and liquid jets, a homogeneous fine-dispersed gas-droplet flow is formed [9]. At the same time, the air is forced into the combustion zone. The initial ignition of the mixture is carried out by an external gas burner. A stable flame is formed at the burner exit. When the carbon of the fuel interacts with steam in the combustion zone, a gasification reaction takes place with the formation of water gas. This increases the level of carbon burnout and reduces CO and NOx.

3. Experimental methods
In this work, the influence of the excess air ratio on the combustion of liquid hydrocarbons in the presence of superheated steam was studied. Measurements of heat release, the composition of equilibrium, and intermediate combustion products, and flame temperature were carried out.

A flow calorimeter [6] was used to measure the heat capacity W at different regime parameters. The flame of the burner device was introduced into the inner channel of the calorimeter after establishing a constant temperature difference between the coolant at the inlet and outlet. The temperature of the coolant (water) was measured at the inlet and outlet of the calorimeter in a steady-state thermal regime using chromel-alumel thermocouples. Heat release ($q$) during fuel combustion was determined in the
steady-state mode of the device as the difference between the thermal energy received by the working medium from the reaction products and the energy spent to maintain the process (per unit time).

Gas composition was measured using Test-1 (Russia) and Testo 350 (Germany) gas analyzers. Test-1: CO (0–10 % vol.), H₂ (0–40 % vol.), C₆H₅ (0–20 % vol.), CO₂ (0–20 % vol.), O₂ (0–21 % vol.). O₂ was detected by an electrochemical sensor (absolute error of 0.2 % vol.), H₂ by a polarographic sensor (relative error of 5%), each component – CO, CO₂, C₆H₅ – was detected by an optical sensor with an absolute error of 0.2 % vol. (for CO₂ up to 7% vol.), above this value, the main error of the sensor was a relative deviation within 5%. Testo 350: CO (0–500ppm), NO (0–300 ppm), NO₂ (0–500 ppm), CO₂ (0–50 % vol.), O₂ (0–25 % vol.). An electrochemical sensor was installed in the device to measure O₂ (absolute error of 0.2% vol.), CO₂ was determined by an optical sensor with an absolute error of 0.3% vol. and a relative error of 1% when measured up to 25% vol., and above this value with an absolute error of 0.5% vol. and a relative error of 1.5%. Nitrogen oxides NO content was registered by the device as a sum of NO and NO₂ concentrations. An electrochemical sensor was installed in the device for each of these components with an absolute error of 2 ppm for NO up to 40 ppm and a relative error of 5 % for NO over 40 ppm; with absolute error for NO₂ of 5 ppm for measurements of up to 100 ppm and above with a relative error of 5%.

The equilibrium reaction products were taken at the calorimeter outlet, where the combustion products had room temperature. The gas from the flame was taken by a special cooled probe (the inner channel diameter of 2 mm). The combustion products were cooled to room temperature to "freeze" the processes and obtain reliable data on the gas composition of the intermediate components in the flame [10]. Gas sampling was carried out at the burner along the flame axis.

The sampling time at the point was 90 sec, and the frequency was 1 Hz.

Measurement of the average temperature in the flame was carried out using a Pt-Rh/Pt-Rh thermocouple (relative error of 0.5%), according to the method [10], in the same points where gas was taken. Radiation losses from the thermocouple surface, which reached 200 degrees (or 15% of the measured value), were taken into account. For this purpose, according to [11], the following formula was used for bead thermocouples:

$$\Delta T = \frac{1.25\varepsilon d^3(T_e^4 - T_a^4) \left( \frac{\eta}{\rho V} \right)\frac{1}{\lambda}}{\lambda},$$

where $T_e$ is the temperature measured by the thermocouple, $T_a$ is the ambient temperature, $\varepsilon$ is the emissivity of the thermocouple, $\sigma$ is the Stefan-Boltzmann constant, $d$ is the diameter of the thermocouple, $\lambda$, $\eta$ are the coefficients of thermal conductivity and viscosity of the gas, and $\rho$, $V$ are the density and speed of the gas. Due to the lack of accurate information about the composition of the complex mixture in the flame, according to [11], the composition of the gas mixture has no significant influence on the value of radiation. Therefore, the parameter values for air are used.

Water heating and steam superheating were carried out by an electric steam generator [12]. The water flow rate was set by a plunger dosing pump. The fuel flow rate was regulated by the Bosch automobile fuel injector. The air flow rate was determined using the Dwyer rotameter.

4. Measurements conditions

Diesel was used as a fuel: density of 840 kg/m³, viscosity of 4.1 cSt, carbon of 84.6%, hydrogen of 13.6%, sulfur of 0.4%, and nitrogen of 0.6%.

For the study, we chose a mode in which the burner with uncontrolled air supply into the combustion chamber has minimal CO and NOₓ emissions at 10 kW power [6]: fuel flow rate $F_f = 0.8$ kg/h and superheated steam flow rate $F_s = 0.4$ kg/h, i.e., the mass concentration of steam in the mixture with the fuel was 33.3%. The temperature of superheated steam was set constant to 260°C, and the superheating ~110°C.

According to the EN 267 standard [13], the stoichiometric value of the amount of air required to burn 1 kg of diesel fuel is obtained. This value is equal to 14.45 kg of air. It should be noted that in the
investigated burner, the combustion air is fed both into the combustion chamber forcibly, and is entrained by the external flame from the environment (since the burner is atmospheric). According to numerical calculations [14], in the burner with free air inflow, there is approximately the same amount of air entrained into the combustion chamber and by the external flame. Thus, it may be assumed for the investigated burner, i.e., at a fuel flow rate of 0.8 kg/h, it is required to supply about 6 kg/h of air into the combustion chamber. However, the limits of air consumption in the investigated burner, which are lower than the “stoichiometric” one, are established from experience. When the air flow rate is less than 0.85 kg/h, flame-out accompanied by pulsations is observed due to the lack of oxidizer in the burner combustion chamber, necessary for ignition of fuel. Above the flow rate of 2.8 kg/h, the internal aerodynamics in the combustion chamber is disrupted. Air supply under pressure (>1.5 bar) into the combustion chamber disrupts the structure of the gas-droplet flow in the ignition zone, destroying the recirculation area near the nozzle, which is the flame stabilizer during the burner operation. Thus, the values of burner air consumption of 0.85, 1.7, and 2.8 kg/h (at room temperature) chosen for the research correspond to the excess air ratio in the combustion chamber \(\alpha = 0.07 \div 0.24\). In calculating these values, steam oxygen is not taken into account, since its degree of dissociation in the combustion chamber is not known. The total mass amount of oxygen contained in the superheated steam at a flow rate of 0.4 kg/h is 0.36 kg/h, so that the \(\alpha\) value in the combustion chamber can change by 0.1 at most.

5. Results and discussion

In the experimental studies, we have obtained the values of temperature in the burner flame, the gas composition of equilibrium and intermediate combustion products, and heat release during combustion of diesel fuel in a new steam-oil burner with a forced air supply.

Figure 2 shows the flame photographs at different air flow rates in the combustion chamber. The air flow rate has no noticeable effect on the flame, which is 20 cm long. The flame color is predominantly yellow, with blue shades at the base.

![Figure 2](image)

Figure 2. Combustion of diesel fuel at different air flow rates into the combustion chamber (kg/h): (a) 0.85 kg/h; (b) 1.8 kg/h; (c) 2.8 kg/h.

Figure 3 shows the temperature profiles along the symmetry axis of the burner flame. For the studied modes the temperature profile has the same shape, and the maximum temperature (1650–1700 °C)
is located in the center of the flame at a distance of 10 cm from the edge of the burner. As the air flow rate increases, the flame temperature rises noticeably. Figure 4 shows the results of gas analysis of intermediate combustion products in the flame. For the studied modes, the profiles of the individual gas components have a similar form. The maximum values of intermediate components ($C_nH_m$, $H_2$, and CO) are observed at the base of the flame when they leave the burner. The region of maximum temperature in the flame corresponds to the minimum values of oxygen $O_2$ (1–2 vol.%). As the air flow rate in the combustion chamber increases, there is a rise in nitrogen oxides $NO_x$ in the flame (from 25 to 60 ppm), caused by an increase in the flame temperature. The higher air flow rate in the combustion chamber contributes to faster combustion of $C_nH_m$, which is indicated by lower values of hydrocarbons at a higher excess air ratio. The CO content in the flame reaches 7 vol.%. 

Fig. 5 shows the gas composition of equilibrium combustion products at the calorimeter outlet. The content of toxic nitrogen oxides and carbon monoxide in the equilibrium combustion products corresponds to the standard EN 267: $NO_x$<60 ppm, CO<55 ppm. When the excess air ratio rises in the studied range of values, the CO content increases by 40%.
The released heat obtained by the calorimeter taking into account the radiation losses (~0.7 MJ/kg) is 43.4 MJ/kg, which is close to the highest heat of combustion of the diesel fuel (44.9 MJ/kg) and indicates the effectiveness of the burner.

Conclusions
The possibility of controlling the air flow rate in the combustion chamber of a new atmospheric burner for the combustion of liquid hydrocarbons with steam supply in the combustion zone has been provided. The influence of the excess air ratio in the combustion chamber of the burner device on the thermal and environmental performance of diesel fuel combustion has been studied. For the first time, the results of gas analysis of equilibrium and intermediate combustion products and temperature measurements have been obtained.

For the gas composition of the intermediate combustion components along the flame symmetry axis, similar profiles are observed, and the temperature profiles also are similar. As the air flow rate in the combustion chamber increases, the maximum temperature is higher, and the nitrogen oxides NOx in the flame rise. At the same time, the content of toxic nitrogen oxides and carbon monoxide in the equilibrium combustion products meets the standard EN 267.

The air flow is found to have no noticeable effect on the flame form, and the released heat for the studied modes is close to the higher heat of combustion of the diesel fuel, which indicates the efficiency of the burner.

The results obtained may be used in mathematical modeling for creating burner devices that ensure high combustion efficiency with low emissions of harmful substances.

Acknowledgments
The study was financially supported by the Russian Science Foundation (project No. 18-79-10134).

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