Diesel fuel combustion under steam gasification conditions

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Abstract. By the example of diesel fuel, the combustion of liquid hydrocarbon fuel in a burner device with a forced controlled steam supply is experimentally studied. Spraying of liquid fuel is provided as a result of its interaction with a high-speed jet of superheated steam, without fuel contact with the atomizer. This method of dispersion has significant technological advantages in the use of substandard liquid fuels. These are associated with the prevention of clogging of the atomizer and fuel supply channels, which improves the performance and reliability of the burner device. The composition of combustion products and the specific heat power are studied in a wide range of changes of the operating parameters of the burner device (steam flow rate and fuel consumption). The regimes under which high fuel combustion completeness is ensured at low content of harmful emissions in gaseous reaction products have been found.

1. Introduction

In devices for organic fuel combustion, water (or steam) is used to reduce the thermal load and to suppress detonation in combustion chambers, to ensure dispersion of heavy fuels [1], and to create water-fuel emulsions [2-4]. The use of water is a known way to reduce NOₓ concentration [5]. The reason of suppressing the NOₓ production is usually a reduction of the flame temperature by increasing the heat capacity of the combustible mixture in the presence of water vapor. During combustion of syngas in gas-turbine units, steam provides the greatest reduction of NOₓ emissions in comparison with such diluents as CO₂ and N₂ [6-9]. In contrast to the processes in gas turbine units, the effect of steam on the combustion of liquid hydrocarbons has not been fully studied today. There are some studies on the influence of steam on the performance of kerosene spray combustion, including the content of NO in the combustion products [10, 11]. However, a number of important issues remain open and require further study.

IT SB RAS proposed the method of combustion of liquid hydrocarbon fuel in a superheated steam flow [12], at which gasification of carbonaceous particles of incomplete combustion of liquid hydrocarbons takes place. The evaporative burners were used to show [13, 14] significant influence of water vapor on the main characteristics of the process. This combustion method ensures stable ignition, high fuel combustion completeness and low content of toxic components in combustion products. This approach is promising for the environmentally safe disposal of low-quality liquid hydrocarbon fuels and combustible industrial waste with the production of thermal energy.
2. Experimental setups and measurement methods

To continue previous studies [13, 14] this paper experimentally investigates the process of diesel fuel combustion in a spray-type burner with a forced controlled steam supply (figure 1). Liquid fuel dispersion is provided as a result of interaction with a high-speed jet of superheated steam without fuel contact with the atomizer. This method of dispersion has significant technological advantages in the use of substandard liquid fuels, associated with the prevention of clogging of the atomizer and fuel supply channels, which improves the performance and reliability of the burner device.

Laboratory sample burner is made of AISI 304 steel. The main components of the burner are the housing, together with the output nozzle forming a gas generation chamber; the installation surface; an atomizer (diameter of 0.5 mm) with a holder and a steam line; and a fuel line with a fuel receiver. The outer diameter of the burner is 60 mm, the height is 140 mm, and the outlet diameter is 25 mm. The fuel supply tube is installed at an acute angle to the horizon, and the end of the tube is located in close proximity to the base of the steam jet and has a chamfer (figure 1-a). The design of the burner device ensures a stable supply of fuel and further formation of a homogeneous gas-droplet flow. The design provides a natural air inflow from the atmosphere into the reaction zone through the holes in the lower part of the housing. Atmospheric air is necessary to ignite the liquid. Fuel is supplied to the burner through the fuel line. The steam atomizer connected to the external steam generator (opening angle of 17°) is coaxially installed at the base of the gas generation chamber and is oriented vertically upwards.

The burner is equipped with fuel dosing system, fuel heating system, water dosing system, and electric steam generator. Stable mass fuel flow rate (up to 2 kg/h) is set by the fuel injector and the pump, and the mass is controlled by electronic scales Acom PC-100W-10H (maximum permissible error of 1 g). For high viscosity fuel, heating (up to 110 °C) and primary filtration systems are used. The electric steam generator (average power intake of 1.5 kW) allows obtaining superheated steam at the output with the following parameters [114]: temperature up to 550 °C, pressure up to 1 MPa, and mass flow rate up to 1.6 kg/h. The steam temperature is measured on the walls of the steam generator by means of chromel-alumel thermocouples of K type. The pressure is controlled using a digital pressure sensor OWEN PD-100 (accuracy of 1 kPa). Stable water supply to the steam generator is

![Figure 1. Burner: (a) scheme; (b) characteristic mode of diesel fuel combustion.](image)
provided by a plunger dosing pump ND 0.5R 1.6/100 K14A (accuracy class – 0.5) with flow rate up to 1.6 l/h. The water weight is controlled using electronic scales Acom PC-100W-5 (maximum permissible error of 0.5 g).

The following scheme of dispersion and combustion of liquid fuel is implemented in the burner device. The high-speed jet of superheated steam flows out of the steam atomizer into the gas generation chamber. Liquid fuel inflows through the fuel supply tube into the base of the steam jet, resulting in a uniform fine-dispersed gas-droplet flow. In addition to fuel spraying, the superheated steam increases the temperature of the fuel drops, which intensifies the mass transfer and mixing, contributing to sustainable ignition. Ignition of the dispersed fuel at the beginning of the process is realized by an external gas burner through the air holes in the lower part of the housing. As a result of the jet inflow to the inner plane of the nozzle, the recirculation region is formed in the peripheral zone (figure 1-a), where ignition is initiated at start-up and the steam-oil jet ignition is stabilized during the device operation. At the same time, steam gasification of thermal decomposition products occurs in the combustion zone, which also increases the combustion indicators of liquid hydrocarbons. The resulting combustible mixture of CO and H\textsubscript{2} burns out in the torch, mixing with oxygen from the atmosphere.

Useful power is an indicator of the energy efficiency of the burner. In the steady-state operation of the device, it is defined as a difference between the thermal energy obtained by the working body from the reaction products, and the energy spent on maintaining the process (per time unit). Energy losses to the environment obviously reduce the useful capacity of the burner. A flow calorimeter was used to measure thermal power at various regime parameters [13]. The torch of the burner device was introduced into the internal channel of the calorimeter after establishing a constant water temperature difference at the inlet and outlet. The temperature of the coolant (water) was measured at the inlet and outlet of the calorimeter at steady-state thermal conditions, using chromel-alumel thermocouples. The characteristic time of thermal relaxation of the calorimeter was about 6.5 min. Volumetric flow of water was regulated by the valve and was recorded using the flowmeter (limits of relative error of 2 \%). In the experiments the volumetric flow rate of the coolant was about 400 l/h, which provided the temperature difference of water at inlet and outlet of no more than 50\textdegree C. The volumetric flow rate and the temperature of the gases leaving the calorimeter were measured using the thermoanemometer Testo 4251, (the velocity measurement error was \pm (0.03 m/s + 5 \% of the measuring value), and temperature was \pm 0. 5\textdegree C). The gas flow temperature at the calorimeter outlet was close to the ambient temperature.

TESTO 350 gas analyzer (error of 5\%) was used to control the composition of gaseous combustion products. Sampling of reaction products was carried out at the calorimeter output.

3. The measurement results and their analysis
Experiments to measure the composition of combustion products and to determine the heat release were carried out at different operating modes of the burner. For a given fixed $\gamma = F_i/F_f$, the steam flow rate $F_i$ was changed in the range of 0.2–1.4 kg/h (which corresponds to the working range of flow rates of the used dosing pump), and the fuel flow rate $F_f$ varied as well. Earlier, on the burner of evaporation type, the effect of the superheated steam temperature on the concentration of CO and NO\textsubscript{x} in combustion products had not been identified, so measurements were carried out at a constant (optimal from the point of view of energy consumption) temperature of superheated steam 250 \textdegree C (deviation within \pm 5\%). Absolute pressure of steam depending on $F_i$ was 0.4\textperthousand 1.0 MPa, and steam superheating reached 100\textdegree C.

Figure 2 presents the results of processing of the received experimental data for two values of the relative steam flow rate $\gamma = 0.6$ and $\gamma = 0.7$, at which stable burning of the used fuel is ensured in almost entire range of steam flow rate. The analysis of the results shows that the specific amount of heat $q$ (per 1 kg of burnt fuel) and the concentration of CO in the combustion of dispersed diesel fuel with the supply of superheated steam jet significantly depend on the steam flow rate (including the flow velocity) and the fuel flow rate (the burner power) in the burner design under study. The
maximum value of $q$ up to 45 MJ per 1 kg of fuel (figure 3-a), which is close to the highest completeness of diesel fuel combustion, is reached at steam flow rate $F_v \sim 0.8$ kg/h for the studied regimes (figure 2-a). This indicates that at such steam flow rate, the jet has a speed that provides the most efficient fuel dispersion and the forming of a reacting flow, where high fuel combustion completeness is achieved. Results of gas analysis (figure 2-b) show that the lowest content of the toxic CO in the exhaust gases (not more than 10 ppm) is observed at $F_v = 0.8$ kg/h. Further increase in steam flow rate at a fixed $\gamma$ leads to fuel underburning: the value $q$ decreases (figure 2-a), and the concentration of CO increases sharply (figure 2-b), exceeding the upper limits of the device measurements (for CO – 500 ppm). The upper limits of $q$ measurements are limited by the capacity of the burner – 20 kW. The lower limits of $q$ (figure 2-a) are close to the combustion failure, and these modes are also characterized by a low value of $q$ and a sharp increase in the concentration of CO in combustion products (figure 2-b).

The obtained results are qualitatively similar for both studied values of $\gamma$. It may be assumed that for the given conditions the steam flow rate is a determining parameter. However, it is important to note that the optimal parameter of steam flow rate and fuel consumption depends on the specific design of the burner, and primarily on its size.

4. Conclusion
The main characteristics of the diesel fuel combustion in a laboratory sample of the original straight-flow burner at fuel spraying by a superheated steam jet have been investigated. The influence of regime parameters (steam flow rate and fuel consumption) on the main thermal and environmental indicators of fuel combustion has been studied. The analysis of the results has shown that at the steam flow rate of 0.8 kg/h the maximum useful heat release up to 45 MJ per 1 kg of fuel is reached (at the power of 14-16 kW). Comparison of this value with the highest calorific value of diesel fuel testifies to high combustion completeness. At that, the low content of toxic components in combustion products, [CO] < 10 ppm, is noted.

The experimental data obtained by the example of diesel fuel allow organizing the optimal operating modes of the burner device under study and confirm the prospects of the proposed method of dispersion and combustion of liquid hydrocarbons in a superheated steam flow and the principal possibility of achieving high environmental performance and energy efficiency in the disposal of substandard fuels and industrial waste with obtaining thermal energy. Further research is expedient to carry out with substandard liquid hydrocarbons, such as, waste oil, heating oil, and crude oil.

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