Investigation of high speed steam jet effect on combustion of substandard liquid hydrocarbons

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Abstract
Combustion of liquid hydrocarbon fuel dispersed by superheated steam jet was experimentally studied. Characteristics of the combustion process (heat release, emission of toxic products, flame temperature) were investigated in a laboratory direct-flow atmospheric burner (capacity up to 20 kW) at different operating systems with waste transmission automotive oil as fuel example. Regimes were found which provoke stable combustion of non-quality liquid hydrocarbons. It was shown dependences of heat, flue gas parameters on superheated steam flow rates, fuel flow rates, flame temperatures.

Introduction
It is known that adding water to the process of burning organic fuel can be used in different ways. One of them is to disperse heavy fuels, suppress detonation in combustion chambers and reduce heat load [1]. Also, it can be applied at water-fuel emulsion creation [2-4]. In addition, to reduce the concentration of NOx [5] by lowering the flame temperature, water is also used. This is due to the fact that in the presence of water vapor there is an increase in the heat capacity of the combustible mixture. At considering the use of the technology in gas turbines some researchers note that water vapor has the greatest effect on suppressing the formation of thermal NOx compared to CO2 and N2 when using the technology of recirculation of waste gases [6-9]. But when considering works that investigate water influence on liquid fuel combustion, for example, articles with study with kerosene spray [10, 11], it can be noted that this point is not fully understood today. Many important questions are still open and require further study.

A method of combustion liquid hydrocarbons in a superheated steam presence [12], based on gasification of liquid hydrocarbons incomplete combustion carbon-containing particles, was proposed and investigated on evaporator-type burners in works [13, 14]. It was shown that superheated steam positively affects on the main combustion characteristics: stabilization of the ignition, increase combustion efficiency, decrease the content of flue gas toxic components. This method can be used for environmentally friendly disposal of low and non-quality liquid hydrocarbons and combustible industrial waste with heat produce. Despite the positively steam effect, utilization of high viscosity fuel in evaporative burners is difficult due to relatively fast coking of burner surfaces. Therefore, to
burn off-grade liquid hydrocarbons in the steam gasification mode, it is necessary to develop and research fundamentally different ways of supplying fuel and mixing it with water vapor.

One of the promising methods of spraying substandard liquid hydrocarbons is a technical solution based on the interaction of a liquid with a high-speed steam flow without contact of the fuel with a nozzle [15]. This method of dispersion has significant technological advantages when using substandard liquid fuels associated with preventing coking of the nozzle and clogging of the fuel supply channels, which improves the performance and reliability of the burner.

In the present work, combustion of liquid hydrocarbon fuel dispersed by superheated steam jet was experimentally studied in a laboratory burner device (capacity up to 20 kW).

In this paper, the process of burning liquid hydrocarbons sprayed by a superheated steam jet is experimentally studied using the waste transmission automotive oil as an example. The main goal of the research is to study the effect of regime parameters on the characteristics of the combustion process.

**Experimental equipment and methods**

The investigation was conducted on an experimental setup, which consists of a steam and fuel supply systems. The steam with necessary parameters (flow rate up to 1.4 kg / h, temperature up to 550 °C) is produced by an electric steam generator (there are three heated elements with a summary power consumption of 2.2 kW). The water, which is required for steam generating, is provided by a plunger dosing pump ND 0.5R 1.6/100 K14A (accuracy class - 0.5). The fuel (up to 2 kg / h) is supplied by a fuel pump thought prefilter and dosed by a fuel injector. In case of high fuel viscosity, a heating system is applied (up to 110 °C). To control the steam and fuel flow rates, Acom PC-100W-5 and Acom PC-100W-10H electronic scales (limit of permissible errors are 0.5 g and 1 g) are used.

Fig. 1 shows the photograph and the scheme of work of the atmospheric burner laboratory sample. The burner device (Fig. 1) includes several main components. They are: a gas generation chamber, consisting from a body and an output nozzle; a base with installed coaxially in the center and oriented vertically upwards a steam nozzle (diameter 0.6 mm, the opening angle of 17°), connected to a holder with a steam line; a fuel pipeline with a receiver. The device size is 50 mm in external diameter, 140 mm in the height. The outlet nozzle has a diameter of 25 mm. The fuel pipeline is a tube with a beveled end. It is placed at an acute angle to the burner base that this end is placed close to the steam jet base. This design allows supplying a steady fuel flow rate for further formation of a quality homogeneous gas-droplet flow. Also, the gas generation chamber lower part has holes providing an air supply from the atmosphere into the reaction zone for fuel ignition in the device. The steam nozzle connected through the holder with the steam line to the electric steam generator. Thus, the laboratory direct-flow atmospheric burner has the following scheme of liquid fuel spraying and burning. The water pump supplies water with a given flow rate to an electric steam generator heated to the desired temperature. The produced steam flows from the nozzle in the burner and heats it. The power control system of the steam generator ensures desired superheated steam temperature. A liquid fuel with a given flow rate is supplied through the fuel tube into the steam jet base, as a result, a uniform fine gas-droplet flow is formed. In addition to spraying the fuel, superheated water vapor raises the temperature of the fuel droplets, which intensifies the mass exchange and the mixture formation, contributing to steady ignition. Also, a recirculation area is formed in the peripheral zone near the inner plane of the outlet nozzle due to jet structure. In this way here ignition is initiated during start-up and the ignition of the steam-oil jet during device operation stabilizes. At the same time, in the combustion zone, steam gasification of the products of thermal decomposition of the fuel (H₂O + C→CO + H₂) occurs, which also influences the combustion process. The resulting combustible mixture of CO and H₂ mixing with oxygen from the external atmosphere burns in the flame. The burner design is protected by RF patent [15].

Parameters, which were experimentally studied and used to analyze the characteristics of the combustion method of liquid fuels, were: heat release, flue gas composition and flame temperature.
Heat ($q$) and the thermal power $W$ of the combustion of the waste transmission automotive oil sprayed by superheated steam was measured by a flow calorimeter [13] at different burner regimes. The burner flame was inserted into the internal channel of the calorimeter after establishing a constant difference in water temperature at the inlet and the outlet. The temperature of the coolant (water) was measured at steady state thermal conditions by using chromel-alumel thermocouples at the inlet and outlet of the calorimeter. All results were recalculated as the difference between the thermal energy received by the calorimeter (calculated by heat equation) and the energy spent on maintaining the process (per unit time) [13].

![Fig.1. The burner device scheme](image)

The flue gas composition ($O_2$, $CO$, $NO$, $NO_2$, $SO_2$, $CO_2$) was controlled by a TESTO 350 gas analyzer (5% error). A sampling of the reaction products was carried out at the exit of the calorimeter.

To control the burner operation modes, the flame temperature was measured using a platinum-rhodium-platinum-rhodium thermocouple (0.3 mm diameter). Temperature profiles were measured in an external plume in the plane of symmetry of the burner. The thermocouple was moved using an automated coordinate-moving device (spatial step 10 mm along the torch and 3 mm in the radial direction, the measurement time at the point was at least 10 s, the delay time before measurements at the point was 7 s).

**Results**

Experiments on the measurement of heat generation, emission of toxic products and flame temperature were carried out at various operating burner regimes: at the steam mass flow rate $F_v$ 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 (deviations when adjusting from the given average values of rates - within 5% for steam and 2.5% for fuel). The range of $F_v$ values corresponds to the working range of the water pump, as well as the performance of the laboratory steam generator, necessary for overheating the steam to a predetermined temperature. The limits of fuel flow rate $F_f$ correspond to the allowable power of the burner during laboratory measurements.

It was previously established [16] that the temperature of superheated water vapor has a weak effect on the main indicators of liquid fuel combustion, so the measurements were carried out at a constant steam temperature $T_v = (260\pm10)°C$, which ensures sufficient steam overheating for the reaction and – minimum energy consumption for steam overheating.
At the measurements waste transmission oil was used (density - 863.25 kg/m³, viscosity - 41.8 mm²/s, the highest calorific value - 45.318 MJ/kg, C - 85.6%, H - 13.2%, S - 0.6% (by weight)). Measurements were carried out for characteristic regimes in the region of stable combustion along the line $\gamma = 0.6$ (Fig. 2), where $\gamma = F_v/F_f$ is the relative mass flow rate of steam. The oil was preheated to a temperature of 60°C to reduce the viscosity.

Fig. 2 also shows a map of the CO concentration in various modes of operation of the burner. The boundaries of the flameout area are based on the results of visual observations of flameout, which depends on the oxidizer/fuel ratio. An approximating straight line was also constructed for the minimum values of CO: $F_v = 1.2F_f - 0.7$ (relationship of steam supply for various power modes of the burner operation).

![Fig.2](image1)

**Fig.2.** The map of CO concentration at the waste automotive oil combustion in a jet of superheated steam at $T_s = (260 \pm 10)$°C.

Fig. 3 shows the dependences of heat generation $q$, useful heat power $W$, the amount of CO and NO$_x$ per 1 kWh of released thermal energy and the temperature of the external flame $T$ from the steam flow rate at a constant parameter $\gamma = 0.6$. The maximum value $q \sim 44$ MJ/kg is achieved with a burner power $W = 14$ kW and steam flow rate $F_v = 0.7$ kg/h (Fig. 3-a); fuel combustion efficiency ratio = 97%. At the same time, the minimum amount of CO and NO$_x$ ($\{CO\} = 20$ mg / kWh, $\{NO_x\} = 60$ mg/kWh) is achieved, Fig.3-b. In the area of increasing the $\{CO\}$ value, the $q$ values decrease sharply, which indicates incomplete combustion of the fuel. $\{NO_x\}$ values decrease with an increase in steam flow rate (Fig. 3-b), because the combustion occurs at low air consumption. The maximum temperature in the torch reaches $\sim 1330$°C (Fig.3-c).

![Fig.3](image2)

**Fig.3.** Dependencies of $q$, $W$, contents of $\{CO\}$, $\{NO_x\}$ and the temperature level of the external flame $T (T_s = (260 \pm 10)$°C) from steam flow rate at a constant parameter $\gamma = 0.6$. 

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Conclusions

Using the example of waste transmission automotive oil, the process of burning liquid hydrocarbons sprayed by superheated water vapor was experimentally investigated. The experiments were carried out on a laboratory sample of a burner device (up to 20 kW), which implements a promising method of dispersing substandard liquid hydrocarbons due to the interaction of a liquid with a high-speed steam flow, without contacting the fuel with a nozzle. This method has significant technological advantages associated with the prevention of coking of the nozzle and clogging of the fuel supply channels, which improves the performance and reliability of the burner.

The effect of operating parameters (steam and fuel flow rate) on the characteristics of the combustion process is studied: heat generation and composition of combustion products, flame temperature. Depending on the steam and fuel flow rates, a regime map was obtained, including: the flame breaking boundary was established, a stable combustion area and a zone with a high CO content in the combustion products were found, and steam supply dependency was obtained for various power modes, which ensured minimum values CO.

The maximum value of 44 MJ / kg is achieved with a burner power of 14 kW and steam flow rate of 0.7 kg/h, the coefficient of completeness of combustion of fuel is 97%. In this case, the minimum amount (per the released thermal energy) of carbon monoxide 20 mg/kWh and nitrogen oxides 60 mg/kWh is produced. The maximum temperature in the flame reaches 1330°C.

Thus, the possibility of substandard liquid hydrocarbons combustion in a direct-flow atmospheric burner is shown. The advantages of combustion with steam jet atomization allow using the burner for heating low-rise industrial and residential facilities.

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