Steam technology application for liquid hydrocarbons combustion

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Abstract. Crude oil is an attractive fuel for energy production because it does not require the additional costs for processing and, in some cases, transportation. Existing technologies for combusting liquid fuel do not always ensure the achievement of required parameters, in particular, the environmental ones. The authors suggest to use the technology of crude oil burning in the presence of superheated steam as one of the ways to improve environmental performance at hydrocarbon combustion. For this purpose, the design of atmospheric burner with liquid fuel spraying by a jet of superheated steam was modernized. The regimes of crude oil combustion in a modernized burner are determined. The results obtained indicate the efficiency of using the proposed technology for combustion of crude oil sprayed by a jet of superheated steam, as well as the prospects of the developed design of a low-power burner for practical applications.

1. Introduction
Crude oil is an attractive fuel for energy production because it does not require additional processing costs. Thermal power plants on crude oil can be located in close proximity to the oil field [1-2], which also saves the cost of fuel transportation. This is especially important for autonomous heat and power supply in remote and inaccessible regions, including the developed vast Arctic territories. However, crude oil combustion must satisfy a number of requirements, which mainly include high completeness of combustion, reduction of harmful emissions, elimination of solid deposits, etc. [3]. Existing technologies for liquid fuel combustion do not always ensure the achievement of the required parameters, in particular, the environmental ones, when using crude oil. This is due to a number of its features: multifractionality, content of mechanical impurities and water, significant amount of sulfur compounds and nitrogen-containing products, heavy residues [4], which produce combustion products with a high content of soot and toxic components such as NOx and SOx, when being burned.

This work is devoted to the study of burning crude oil in a stream of superheated steam as a promising way to reduce nitrogen oxides (NOx) and increase the completeness of fuel combustion. The novelty of this method of combustion is that the fuel is atomized and burned in a high-speed jet of superheated steam, which ensures the creation of a finely dispersed stream, gasification of carbon-containing products of thermal decomposition of liquid fuel, intensification of interphase mass transfer and chemical reactions, high completeness of fuel combustion with a low content of toxic components in combustion products.
The presence of steam in the combustion zone leads to a decrease in NOx emissions due to an increase in the heat capacity of the mixture during the combustion of hydrogen – air [5] and methane – air [6–8] mixtures. It is shown that the amount of steam or water used, as well as the location and direction of injection play an important role. The question of the influence of the gas-dynamic parameters of steam is also open. So, in [9], the authors note that when steam is injected into the combustion chamber, the NOx content in exhaust gases can be significantly reduced, however, at a high steam flow rate, the tendency to decrease NOx ceases. It was shown in [10] that direct injection of steam into the ignition region, namely, into the region of maximum flame temperature, is most effective for reducing the formation of NOx, [11], in particular, at the end of combustion zone [12]. When burning synthesis gas in a vortex flame, it turned out that water injection (in addition to reducing NOx formation) allows the burning of lean mixtures [13–14]. Positive effects during the injection of water or steam are observed not only for burners, but also for internal combustion engines [15–16]; they occur both during the burning of traditional fuels [17–18], and for various fuel mixtures, in particular ethanol-diesel [19].

This work is aimed at experimental optimization of structural and operational parameters of the promising design of a liquid-fuel atmospheric burner and determination of regularities of fuel combustion under the conditions of steam gasification (in relation to the problem of efficient and environmentally friendly combustion of crude oil). Experimental data are needed, in particular, for testing the CFD models of crude oil combustion.

2. Experimental apparatus and methods
During the experimental studies on crude oil combustion, we used a modernized atmospheric atomizing burner (Figure 1), created on the basis of previously developed 20-kW direct-flow burner for burning diesel fuel and wasted oil. In [20], we described the choice of design and operational parameters of a laboratory burner, studied thermal and environmental characteristics, and showed the advantages.

![Figure 1. Photos of modernized burner: 1 - a combustion chamber corresponding to the design of the original burner [20], 2 - afterburner, 3 - steam supply; 4 - fuel supply.](image)

Crude oil, in contrast to light types of liquid fuel, contains long chains of hydrocarbons [4], whose combustion requires a longer residence time in the combustion zone. Therefore, in this work, we have modernized the burner, based on the principle of staged combustion, which allows organizing more favorable internal aerodynamics. At the outlet nozzle of the original burner we have installed an afterburning unit, inside which a cone-shaped bluff body is located in the center, ensuring flow inhibition and promoting formation of a recirculation zone that increases the degree of fuel afterburning. The afterburner, like the burner, is made of AISI 321 stainless steel (1.4541) and consists
of a cylindrical body (inner diameter 80 mm, height 50 mm), two covers with holes (diameter of the lower hole 25 mm, diameter of the upper hole 40 mm) and conical separator (base diameter 40 mm, height 20 mm). The dimensions of the afterburner, including the location of the divider (the base of the cone is located in the middle of the height of the afterburner), which ensures stable operation of the burner, were chosen due to experimental optimization in the laboratory.

Operation of such burners is based on the use of a promising method of combustion, when the fuel is sprayed by a jet of superheated steam [21]. Superheated steam flows from the nozzle to the burner combustion chamber. Liquid fuel is supplied to the base of the steam jet; as a result, a finely dispersed gas-droplet flow is formed. The recirculation region is formed near the place where the steam flows into the inner plane of the nozzle of the chamber in the peripheral zone; in this zone, ignition is initiated during start-up, and the ignition of the steam jet is stabilized during operation of the device. Flames containing droplets of oil spread from the combustion chamber to the afterburner. Due to the propagation of the reacting stream to the divider, a recirculation zone is formed, which contributes to the combustion of unburned fuel particles. At the outlet of the burner, a stable flame is formed that does not contain fuel droplets, and this increases the completeness of fuel combustion. The design provides a natural flow of air from the atmosphere into the reaction zone through openings in the lower part of the housing. In this regard, its flow rate is not established, but is controlled only by measuring gases in the combustion products (in general, with the air necessary for burning a flame in the atmosphere).

The thermal and environmental parameters of crude oil combustion in a modernized burner were studied in the experimental setup [20, 22], which diagram shown in Figure 2. The installation consists of the following elements: burner; water supply system (flow rate $F_v = 0.2 \div 1.4$ kg / h); electric steam generator (degree of overheating of steam $T_s$ up to 400 degrees); air supply system instead of steam (flow rate $F_a = 0.2 \div 1.0$ kg / h); liquid fuel supply and heating system (fuel consumption $F_f = 0.3 \div 2.2$ kg / h); flow calorimeter that determines the amount of heat generated (accuracy ± 2.5%); Testo 350 gas analyzer measuring the composition of combustion products at room temperature at the outlet of the flow calorimeter (components: CO, CO2, NO, NO2, SO2, O2, accuracy ± 5%); platinum-rhodium-platinum-rhodium thermocouple measuring the flame temperature of the burner (accuracy ± 5%); Automated control system from a PC. The experimental setup for studying the steam-gas mode of burning liquid hydrocarbons is part of the unique research facility of Ural State University “Large-scale thermohydrodynamic setup for studying the thermal and gas-dynamic characteristics of power plants” [23].

![Figure 2. Scheme of experimental setup](image)
3. Measurement results

In experiments with the modernized burner, crude oil from the oil field in the Tomsk Region of the Russian Federation was used; its properties are: density 815 kg/m$^3$; viscosity 6.3 sSt; high heat value 44.24 MJ/kg; mass fraction (% w/w) C=82.8, H=12.3, S= 0.6, N ≤ 0.3.

The experiments were carried out under various operating conditions of the burner. Fuel flow rate $F_f$ was varied from 0.4 to 2.2 kg/h. Steam flow rate $F_v$ was varied from 0.2 to 1.4 kg/h, the steam temperature was constant $T_s = 260 \pm 10^\circ$C (steam overheating was varied from 65 to 110 degrees). It was determined in [20] that the steam temperature has a weak effect on the parameters of fuel combustion; therefore, its value was not varied in the present work.

In the studied range of operating parameters, a change in the maximum temperature reaches 170$^\circ$C, and its maximum value is 1470$^\circ$C. The values of the specific amount of heat obtained from the combustion products in the calorimeter can be divided into two operating ranges: the first is the one where high completeness of combustion of crude oil is ensured ($q \sim 44$ MJ / kg), and the second where it is not provided. In the second area $q$ values decrease sharply, which indicates fuel underburning. In the regimes with the maximum completeness of fuel combustion, the content of nitrogen oxides is $\{NO_x\} <225$ mg/kWh, which corresponds to class 1 of the current standard EN 267 [24]. At that, the $[CO]$ values are minimal within the measurement accuracy of the gas analyzer, ±2 ppm. In addition, it is found that flame-out occurs at a maximum oxygen content of 9–10 vol.%. Using the well-known formula for calculating the coefficient of excess air, we obtain that flame-out is achieved at $\alpha=1.85 \pm 0.05$.

Dependences of the nitrogen oxide and sulfur dioxide contents in exhaust gases in various operating regimes of the burner are shown in Figure 3. It can be seen that with an increase in fuel flow rate there is a reduction in $\{NO_x\}$, and vice versa, with an increase in steam flow rate the opposite effect occurs: a slight growth in $\{NO_x\}$ (Figure 3-a). It was established that an raising in the coefficient of air excess $\alpha$ contributes to an growth in $\{NO_x\}$.

The results of content of sulfur dioxide in the combustion products demonstrates that with an increase in fuel flow rate there is an increase in $\{SO_2\}$, and with an increase in steam flow rate, we observed a decrease in $\{SO_2\}$ (Figure 3-b). In Figure 3-b, the dashed line shows the maximum value of $\{SO_2\}$, which corresponds to the complete conversion of sulfur contained in oil into sulfur dioxide. The highest values of $\{SO_2\}$ are achieved in fuel rich region. A decrease in $\{SO_2\}$ with an increase in steam flow rate may indicate formation of sulfuric acid in the composition of condensate formed in the channels of the flow calorimeter.

![Figure 3](image_url)

**Figure 3.** Concentration of (a) NO$_x$ and (b) SO$_2$ in the products of crude oil combustion and air excess coefficient $\alpha$ ($T_s=260\pm10^\circ$C) at $F_v=0.8$ kg/h and $F_f = 1.2$ kg/h.
A comparison of results in Figures 3-a and 3-b shows that the ratio of \{\text{NO}_x\} to \{\text{SO}_2\} in the combustion products is \(\sim 1:3\). The concentration ratio of nitrogen N and sulfur S in the composition of oil is approximately the same.

4. Conclusion
The process of crude oil combustion by spraying it with a jet of superheated steam in a modernized atmospheric burner is experimentally investigated in the work presented. Modernization consists in the use of an afterburning unit based on the principle of staged combustion, which allows an increase in the degree of flow circulation and, accordingly, more complete combustion of heavy fuel.

Due to experimental optimization of design and operating parameters, the possibility of efficient of crude oil combustion in the developed design of a low-power laboratory burner (of up to 20 kW) is achieved.

Thus, the obtained results indicate the efficiency of using the technology of crude oil combustion being sprayed by a jet of superheated steam as well as the prospects of the developed design of a low-power burner (of up to 20 kW). The presented experimental results can be used to create technologies for the environmentally friendly burning of liquid hydrocarbons and test the CFD models of energy processes.

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