CLEANER CRUDE OIL COMBUSTION DURING SUPERHEATED STEAM ATOMIZATION

by

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Crude oil is an attractive fuel for energy production, since its use does not require additional processing costs. Existing technologies for burning liquid fuel do not always ensure the achievement of the modern ecological and energy performance when using highly viscous and substandard fuels. This relates to unstable ignition and combustion of such fuels in the combustion chamber, relatively fast coking of the burner surfaces, etc. The work deals with investigation of crude oil burning in a flow of superheated steam as a promising way to reduce NO_x and increase the completeness of fuel combustion. The experiments were carried out using an original burner where liquid fuel is sprayed due to interaction with a high-velocity flow of superheated steam. This method of spraying allows the creation of a highly dispersed two-phase flow and prevents nozzle chocking and coking when using substandard fuel and waste. At the same time, steam gasification of products of fuel thermal decomposition allows the reduction of toxic emissions, increasing carbon burnout. The regimes of crude oil burning in a modernized burner that provide high completeness of fuel combustion (~44 MJ/kg) with a low content of NO_x and CO in the combustion products have been determined. The amount of these toxic components corresponds to class 1 of EN 267. The results obtained confirm the effectiveness of the investigated method of fuel spraying by a superheated steam jet for environmentally friendly crude oil burning, including this process in the low-power burners (~15 kW). Such devices can be used for the cleaner elimination of liquid hydrocarbon waste with the receipt of thermal energy.

Key words: *crude oil, superheated steam, atomization, clean combustion, gasification*

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. Cleaner elimination of liquid hydrocarbons recovered during new well testing is also an urgent problem [3]. However, crude oil combustion must satisfy a number of requirements, which mainly include high completeness of combustion, low amount of harmful emissions and solid deposits [4]. Existing technologies do not always ensure the achievement of the modern required energy and environmental parameters, when using crude oil because of unstable ignition and combustion in the

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furnace, fast coking of burner surfaces, *etc.* This is due to oil features: multifractionality, content of mechanical impurities and water, significant amount of sulfur compounds, and nitrogen-containing products, heavy residues [5], which produce combustion products with a high content of soot and toxic components such as NO_x and SO_x, when being burned. The problems of crude oil combustion, associated with the presence of hydrocarbons with different viscosity in its composition, density and boiling point in oil composition, are considered in [6, 7]. Gas corrosion of metals, formation of carbon deposits in furnaces and nozzle coking are the most common examples of negative impact on combustion equipment when using crude oil as a fuel [8]. Therefore, efficient combustion of crude oil requires the development of special technologies and devices that allow an increase in energy performance, reduction in emission of toxic combustion products into the atmosphere and an increase in the service life of the equipment.

The negative effects of crude oil combustion can be decreased by controlling aerodynamics of the process. For example, this can be achieved by using a swirler to stabilize the flow at the burner outlet [9] or using an elongated nozzle to inject liquid fuel into the mixing chamber at the main burner outlet, which reduces underburning and deposits on the surfaces of combustion chamber [10]. Another method is a scheme for crude oil combustion in a strong vortex flow [11, 12] or using rotational nozzles with a high degree of atomization [13]. To combust heavy fuels and oil residues, the combustion technologies with the supply of an increased amount of oxidizing agent to the combustion zone are known [14, 15]. Despite the advantages of these methods, their common drawback is the presence of structurally complex elements in the burner (swirlers, rotational nozzles, *etc.*), the use of which limits the service life of the burners and quality of fuel combustion.

Another approach to cleaner crude oil combustion is the use of water-fuel emulsion [16, 17]. It is known that in internal combustion engines such emulsions based on diesel fuel can reduce NO_x emissions by lowering the cycle temperature [18-20] and amount of soot particles [21-23], as well as fuel consumption due to better combustion [24-26]. The authors of [27-29] associates this with the fact that after fuel ignition, water in the emulsion boils up, local microexplosions occur, small droplets form, fuel evaporation and mixing with the oxidizing agent become faster. Due to this, more complete combustion is achieved. In addition, water facilitates soot reduction due to interaction of carbon with hydroxyl radicals (OH*), and also inhibits the production of thermal nitrogen oxides due to lower flame temperatures. The same advantages of burning the water-fuel emulsion in a gas turbine burner are noted by the authors of [30], and more stable combustion is observed. Oil burning in the form of a water-fuel emulsion provides an increase in the completeness of fuel combustion [31]. Disadvantages of using water-fuel emulsions include a high level of costs for their creation, which limits the economic feasibility of practical application of these technologies. The task of efficient cleaner use of crude oil as a fuel requires a further search for new solutions.

This work deals with investigation of crude oil burning in a flow of superheated steam as a promising way to reduce NO_x and increase the completeness of fuel combustion. The novelty of this method of combustion lies in the fact that fuel is sprayed and burned in a high-velocity jet of superheated steam, which ensures the creation of a finely dispersed flow, gasification of carbon-containing products of thermal decomposition of liquid fuel, intensification of interfacial mass transfer, and chemical reactions, high completeness of fuel combustion at a low content of toxic components in combustion products.

Some studies show that injection of water or steam affects the combustion process like the use of water-fuel emulsions. The presence of steam in the combustion zone leads to a decrease in NO_x emissions due to an increase in the heat capacity of mixture during combustion of hydrogen-air [32] and methane-air [33-35] 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 about the influence of gas-dynamic parameters of steam is also open. So, in [36], the authors note that when steam is injected into the combustion chamber, the NO_x content in the exhaust gases can be significantly reduced, however, at a high steam flow rate, the tendency to a NO_x decrease ceases. It is shown in [37] 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 NO_x, [38], in particular, at the end of the combustion zone [39]. When burning the synthesis gas in a swirling flame, it was found out that the injection of water (in addition to reducing the production of NO_x) allows combustion of lean mixtures [40, 41]. Positive effects at injection of water or steam are observed not only for the burners, but also for internal combustion engines [42, 43]. They occur both during the burning of traditional fuels [44, 45], and for various fuel mixtures, in particular ethanol – diesel one [46].

The efficiency of using superheated steam when burning diesel fuel or waste engine oil in the evaporative burners is shown in the studies performed by the authors earlier [47-49]. The combustion of diesel fuel and industrial waste in a jet of superheated steam allows the achievement of high rates of completeness of fuel combustion with a low content of toxic components in the combustion products. However, combustion of substandard fuel in evaporative type burners is not effective. For such fuels, an original spray-type burner that implements a method of liquid fuel atomization by a jet of superheated steam has been developed [50]. The novelty is that liquid fuel is sprayed directly by a high-velocity steam jet without atomizing the fuel by a nozzle. This method of forming a two-phase combustible mixture has significant technical advantages associated with preventing the possibility of coking and clogging of the fuel supply channels, which improves operational characteristics and reliability of the burner and allows combustion of contaminated fuel and combustible liquid waste. The advantages of the proposed method are shown at the example of diesel fuel [51]: high completeness of fuel combustion and 30% reduction in NO_x are achieved in comparison with the use of compressed air instead of steam. These results were obtained by the authors on a direct-flow burner. To burn heavy and low-quality fuels, the direct-flow design does not provide sufficient residence time in the combustion chamber. To study crude oil burning, a new burner using the described method of fuel dispersion has been developed. Its design is based on the principle of staged combustion and the provision of favorable aerodynamics with flow circulation.

The investigated method of liquid fuel spraying and burning in a flow of superheated steam is promising for improving the reliability, environmental safety and efficiency of technologies for using crude oil, waste, heavy hydrocarbons in the production of thermal energy. This combustion method is based on complex physical and chemical processes: dispersion of liquid, thermal decomposition of fuel, interfacial exchange of mass, momentum, and energy, chemical transformations. The kinetics of these interrelated processes has not been fully studied to date. The spatial structure of the multicomponent inhomogeneous turbulent flow in the combustion chamber also plays a significant role. The available information does not allow a confident forecast about the influence of certain factors on the process and result of combustion under the specific conditions. Thus, obtaining the new experimental data on the influence of the main parameters on the characteristics of the process is an important scientific task.

This work is aimed at investigation of the laws of crude oil burning under the conditions of steam gasification in a wide range of operating parameters, search for and substantiation of new fundamental technical solutions to increase the ecological and energy combustion performance in a liquid-fuel atmospheric burner. New reliable experimental data are required, including those for testing the CFD models of crude oil combustion.

Experimental apparatus and methods

Modernized burner

To perform the experiments on crude oil combustion, we used a new atmospheric atomizing burner, fig. 1, created on the basis of modernization of previously developed 20 kW direct-flow burner for burning diesel fuel and used oil, fig. 2(a). In [51], we described the choice of design and operational parameters of a laboratory burner (external burner diameter of 60 mm, height of 140 mm, and outlet diameter of 25 mm), studied thermal and environmental characteristics, and showed the advantages.

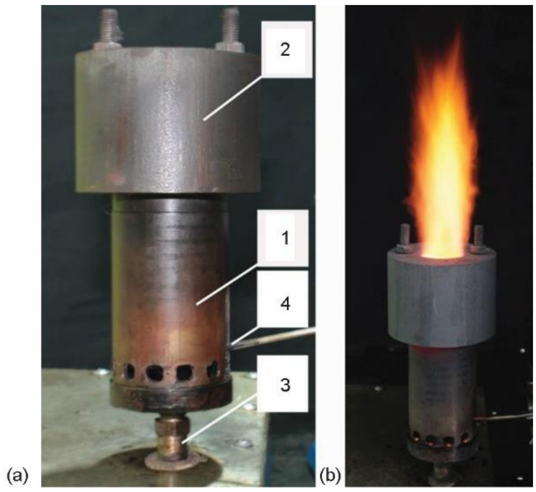

Figure 1. Photos of modernized burner (a) and flame at the outlet of this device (b);
1 – a combustion chamber corresponding to the design of the original burner [51], 2 – afterburner, 3 – steam supply; 4 – fuel supply

The novelty of the proposed method of combustion relates to the fact that fuel combustion occurs in a flow of superheated steam, whose supply to the combustion zone provides steam gasification of carbon-containing products of thermal decomposition and incomplete combustion of liquid fuel, intensification of reaction and carbon burnout. Moreover, the novelty of these burners is connected with the use of a promising method of combustion, fig. 2, when the fuel is sprayed by a jet of superheated steam [42]. This provides a number of advantages:

– it is possible to combust efficiently the substandard liquid fuels and combustible industrial wastes;
– nozzle coking does not occur and faulty operation is prevented due to the separate supply of fuel and steam to the combustion chamber;
– the combustion process is intensified by improving interfacial heat and mass transfer between fuel droplets and superheated steam, which contributes to more intensive evaporation and stable ignition of the fuel;
– concentrations of NO_x are reduced due to a decrease in the flame temperature in the presence of steam in the combustion zone;
– soot formation is reduced due to additional OH radicals formed during steam gasification of thermal decomposition products and incomplete combustion of fuel.

The original burner, fig. 2(a), does not allow high-quality combustion of heavy liquid fuels, including crude oil. Crude oil, in contrast to light types of liquid fuel, contains long chains of hydrocarbons [5], 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, fig. 2(b). 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 afterburning unit, as well as the burner, is made of AISI 321 (1.4541) stainless steel and consists of a cylindrical casing (inner diameter of 80 mm, height of 50 mm), two lids with holes (diameter of the lower hole of 25 mm, diameter of the upper hole of 40 mm), and cone-shaped divider (base diameter of 40 mm, height of 20 mm). The dimensions of the afterburning unit, including the location of the divider (the base of the cone is located in the middle of the afterburning unit height), which ensure stable operation of the burner, were selected due to experimental optimization in the laboratory conditions.

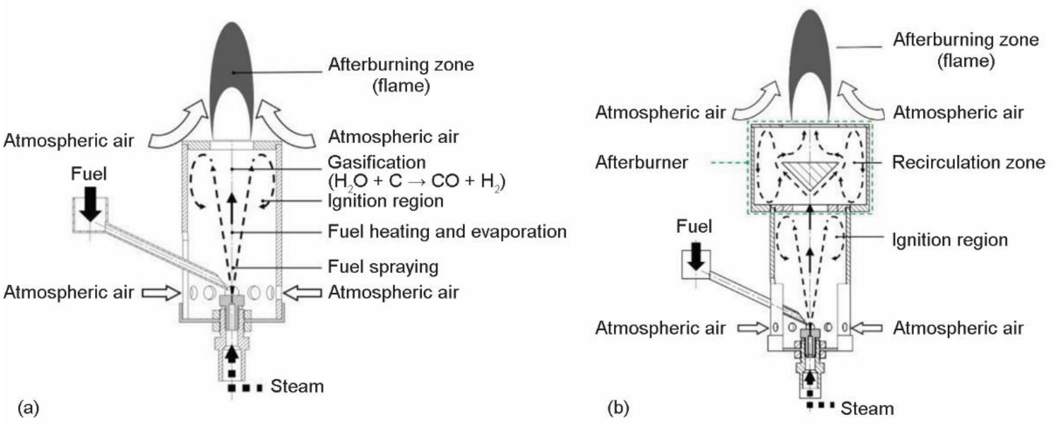

Figure 2. Scheme of combustion in the burner; (a) original burner, (b) modernized burner

The photographs of unburned fuel particles deposited for 10 seconds on a white paper located at a distance of 500 mm from the nozzle are presented in fig. 3. Visual observations demonstrate the effectiveness of afterburner when burning crude oil.

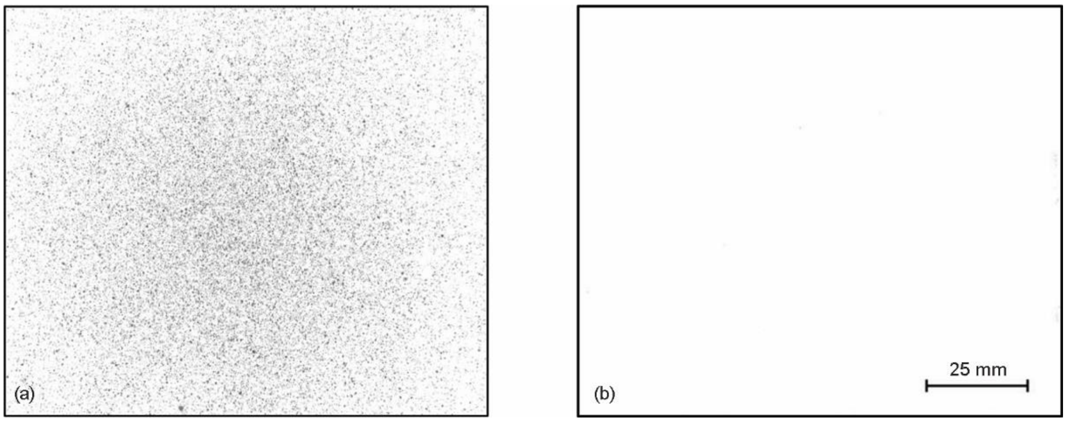

Figure 3. Photos of unburned oil particles; (a) original, (b) modernized

The following scheme for liquid fuel burning is implemented in the modernized burner, fig. 2(b). Superheated steam flows from the nozzle into the combustion chamber of the burner. Liquid fuel is supplied to the base of the steam jet; as a result, a finely dispersed gas-droplet flow is formed. A recirculation region is formed near the place, where steam flows onto the inner plane of the chamber nozzle in the peripheral zone. In this zone, ignition is initiated during start-up and steam jet ignition is stabilized during device operation. A flame containing oil droplets spreads from the combustion chamber to the afterburner. Due to spreading of the reacting flow to the divider, a recirculation zone, which contributes to combustion of unburned fuel particles, is formed. At the outlet of the burner, a stable flame that does not contain fuel droplets is formed, and this increases the completeness of fuel combustion. The design ensures the natural flow of air from the atmosphere into the reaction zone through the openings in the lower part of the casing. In this regard, its flow rate is not set, but only controlled by measuring gases in the combustion products (in total, with air required for flame burning in the atmosphere).

Experimental set-up and measurement methods

The thermal and environmental parameters of crude oil combustion in a modernized burner were studied in the experimental set-up shown in fig. 4. A detailed description of the measurement procedures is given in [48, 51]. The set-up consists of the following elements: burner; water supply system (flow rate F_v = 0.2-1.4 kg/h); electric steam generator (degree of steam superheating T_s of up to 400°); system of air supply instead of steam (flow rate F_a = 0.2-1.0 kg/h); system of liquid fuel supply and heating (fuel-flow rate F_f = 0.3-2.2 kg/h); flow calorimeter determining 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, CO_2, NO, NO_2, SO_2, and O_2, accuracy ±5%); platinum rhodium-platinum rhodium thermocouple measuring the flame temperature of the burner (accuracy ±5%); automated control system with a PC. The experimental set-up for studying the soot-

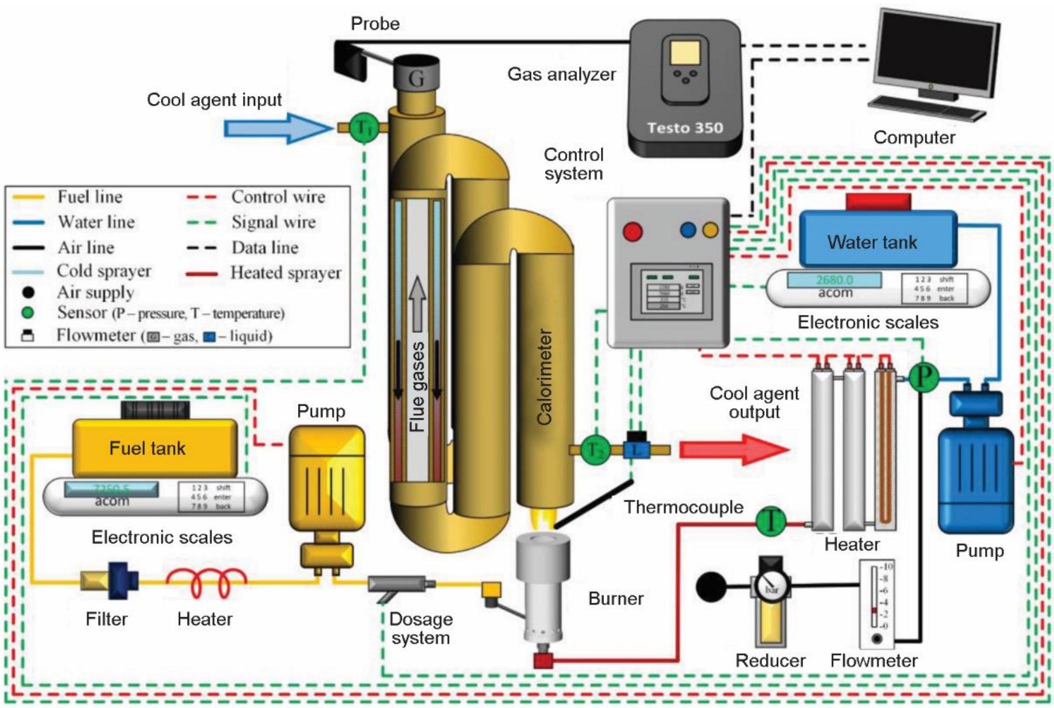

Figure 4. Scheme of experimental set-up

steam regime of liquid hydrocarbon combustion is a part of the unique research facility USU *Large-scale thermo-hydrodynamic set-up for studying the thermal and gas-dynamic characteristics of power plants* [52].

Measurement results

Modernized burner testing

Tests of the modernized burner and evaluation of the efficiency of the afterburner use were carried out on diesel fuel, which burns down easier than oil. Heat release, q, composition of the equilibrium products of combustion, and external flame temperature, T, were determined. To make a comparison, the regime was chosen that ensured, according to [51], high values of q and low {CO} and {NO_x} in the combustion products, tab. 1. The studies were carried out when spraying diesel fuel by a jet of superheated steam and an air jet. When comparing the regimes with steam and air, the equality of volumetric oxygen content [O_2] in exhaust gases was chosen as the determining condition.

Table 1. Parameters of diesel fuel combustion in original [51] and modernized burners

Parameter	Original burner [51]	Modernized burner	
Atomizer	Steam		Air
F_f, [kgh^{-1}]	1.2		
F_v, F_a, [kgh^{-1}]	0.8		0.94
P, [bar]	7.8		7.5
T_s, [°C]	260±10		
q, [MJkg^{-1}]	44.1	44.6	44.2
High heat value, [MJkg^{-1}] [51]	44.95		
W, [kW]	14.7	14.9	14.7
[O_2], [vol. %] (in combustion products)	4.0	1.4	
{CO}, [mgkW^{-1}h^{-1}]	12	3	4
{NO_x}, [mgkW^{-1}h^{-1}]	57	60	90

The test results are shown in tab. 1. According to comparison of parameters of diesel fuel combustion in different burners in the regime of steam supply, for the studied regime there is high heat release q = 44.6 MJ/kg (and useful heat power $W \sim 15$ kW), which is also indicated by low {CO} values. At that, both burners provide a low level of nitrogen oxides in the combustion products at the same level of {NO_x} corresponding to about 60 mg/kWh. The content of oxygen in the combustion products is almost three times less in the modernized burner, its value is 1.4%, which indicates mixture composition close to the stoichiometric one (in the products of combustion [O_2] $\rightarrow$0), and this is accompanied by a decreased {CO} level. Low values of [O_2] are possibly caused by the fact that when the flow is decelerated by the divider, fig. 2(b), the flow velocity in the external flame decreases and, as a result, the amount of atmospheric air entrained by the flame decreases also. Another reason for the difference in [O_2] in the combustion products may be due to the fact that there is no air influx in the afterburner, respectively, less atmospheric air is involved in the reaction.

A comparison of parameters of diesel fuel burning in the regimes with a supply of superheated steam and heated air in a modernized burner showed the following. In the regime with steam supply, more complete combustion of fuel is achieved. As in [51], it is shown that the content of NO_x in the combustion products is 30% higher in the regime with air supply, and in both cases extremely low concentrations of CO are observed, which corresponds to the current environmental standards [53]. Preservation of this trend, regardless of the burner design, allows us to talk about the effectiveness of the considered method for burning liquid hydrocarbons in the presence of superheated steam and prospects of its use for cleaner crude oil combustion.

To compare the results obtained, let us consider the characteristics of one of the models of low-power liquid-fuel burners working on a Diesel engine of the well-known company Weishaupt-WL5-A-H (16.5-40 kW). According to the technical documentation [54], its emissions meet class 2 of the EN 267 standard: $\{NO_x\} \leq 185$ mg/kWh, $\{CO\} \leq 110$ mg/kWh. Thus, the developed burner provides better indicators: nine times lower by CO, and three times lower by NO_x.

Crude oil combustion

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 presented in tab. 2.

Table 2. Physical-chemical properties of crude oil

Properties	Crude oil
Density, [kgm^{-3}]	815.6
Viscosity, [cSt]	6.3
Low heat value, [MJkg^{-1}]	41.62
High heat value, [MJkg^{-1}]	44.24
Elemental analysis	
C, [% w/w]	82.8
H, [% w/w]	12.3
S, [% w/w]	0.6
N, [% w/w]	≤0.3
H_2O, [% w/w]	–

The experiments were carried out under various operating conditions of the burner. Fuel-flow rate, F_f, was varied from 0.4-2.2 kg/h. Steam flow rate, F_v, was varied from 0.2-1.4 kg/h, the steam temperature was constant $T_s = 260\pm10$ °C (steam overheating was varied from 65° to 110°). The limits of F_f correspond to the permissible power of the burner in laboratory measurements. The range of F_v values corresponds to the operating range of the dosing water pump, as well as productivity of the laboratory steam generator, required to overheat steam to a given temperature. It was determined in [51] that the steam temperature has a weak effect on the parameters of fuel combustion; therefore, its value was not varied in the present work.

The maps of vapor content in relation to fuel, CO and oxygen in the chilled combustion products are presented in fig. 5. The boundaries of Region II and $[O_2]$ isolines are plotted based on the measurement results on gas composition at the outlet of the flow calorimeter, fig. 4. Region II is selected conditionally as a working area, where the [CO] is <500 ppm. Region III was not considered in this paper because there is significant underburning of fuel, accompanied by an increase in [CO] in the combustion products. This is associated with mixture overfueling. The boundaries of Region I are plotted according to the results of visual observations of flame-out caused by depletion of the fuel mixture: flame-out is observed in the region of maximum mass concentration of steam in the mixture with fuel corresponding to the value of 50%, fig. 5(a). In addition, it is found that flame-out occurs at a maximum oxygen content of 9-10 vol.%, fig. 5(b). Using the well-known formula for calculating the coefficient of excess air [53], we obtain that flame-out is achieved at $\alpha \approx 1.85\pm0.05$.

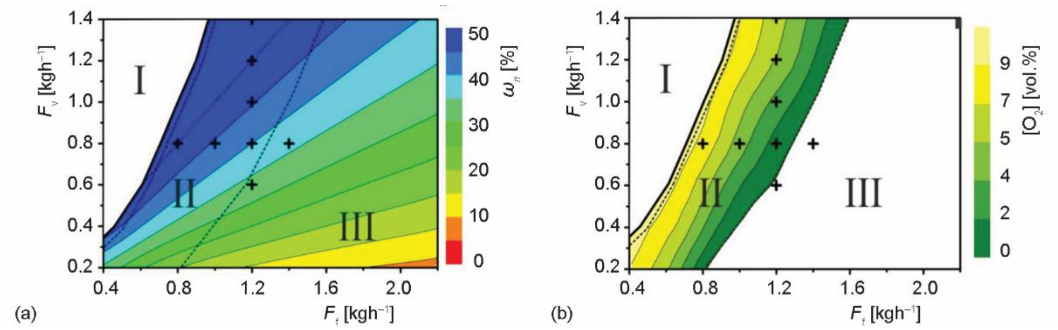

Figure 5. The F_v-F_f diagrams of (a) mass fraction of steam in the mixture with fuel [%] at crude oil combustion in a jet of superheated steam, (b) [O_2] in chilled combustion products [vol.%]: I – flame-out, II – region of steady burning (measuring area), III – flame with a high content of CO in combustion products, [CO] > 500 ppm; symbol "+" indicates the measurement points

The heat-engineering indicators were determined in Region II for the regimes marked in the map, fig. 5.

The values of the specific amount of heat obtained from the combustion products in the calorimeter taking into account the heat losses described in the measuring procedure are shown in fig. 6 [51]. According to the analysis of results, fig. 6, in Region II there is a high completeness of crude oil combustion $q \sim 44$ MJ/kg (see the high heat value of oil combustion in tab. 2), q depends weakly on steam and fuel-flow rate in the studied area. Moreover, the calculated coefficient of excess air, α, lies in the range of 1.0-1.85. In Region III, q values decrease sharply, which indicates fuel underburning.

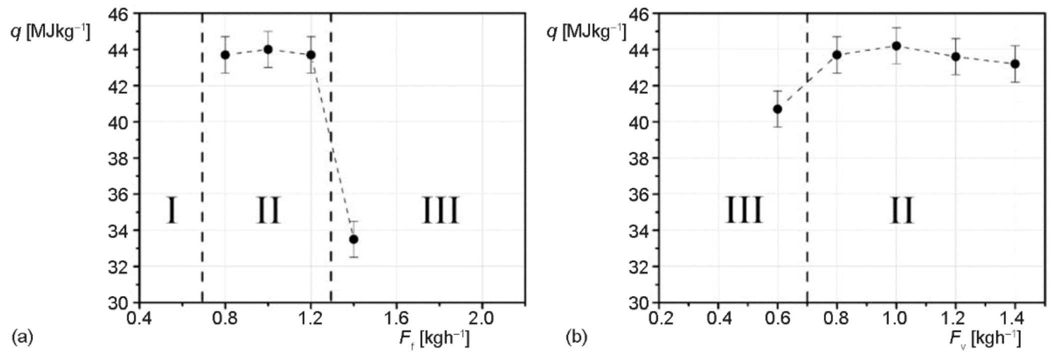

Figure 6. Specific amount of heat, q, produced at crude oil combustion depending on fuel-flow rate F_f (a) and steam flow rate F_v (b) at T_s = 260±10 °C; (a) F_v = 0.8 kg/h; (b) F_f = 1.2 kg/h

Dependences of the NO_x content in exhaust gases in various operating regimes of the burner are shown in fig. 7. It can be seen that with an increase in steam flow rate, fig. 7(b) or a decrease in fuel-flow rate, fig. 7(a), the volume fraction of [NO_x] decreases. However, when recalculating the content of NO_x from ppm to milligrams per unit of heat obtained in the equilibrium combustion products, fig. 7, the inverse dependence can be observed: with an increase in fuel-flow rate there is a reduction in {NO_x}, fig. 7(a), and vice versa, with an increase in steam flow rate the opposite effect occurs, a slight growth in $\{NO_x\}$, fig. 7(b). The same dynamics is observed for the thermocouple measurements in the external flame of the burner, fig. 8: with rising fuel-flow rate, the maximum temperature in the flame reduces, fig. 8(a), and with increasing steam flow rate, the maximum temperature in the flame rises, fig. 8(b). It was established that a raising in the coefficient of air excess, α, contributes to a growth in $\{NO_x\}$ and flame temperature, fig. 7.

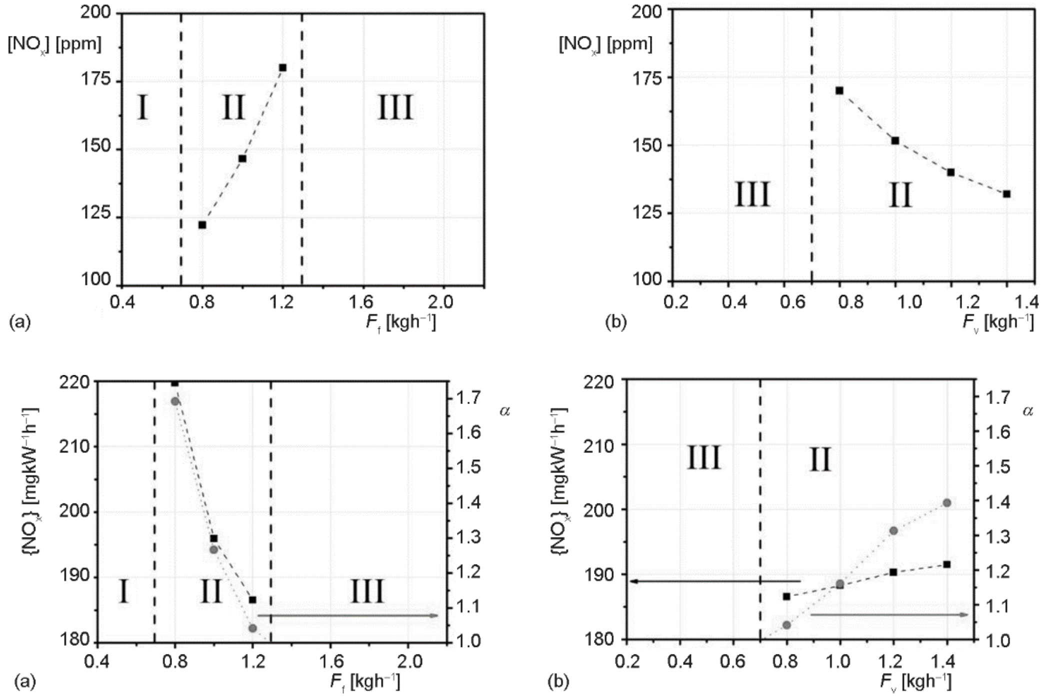

Figure 7. Concentration of NO_x in the products of crude oil combustion and air excess coefficient, α, (T_s = 260±10 °C): (a) F_v = 0.8 kg/h; (b) F_f = 1.2 kg/h

Thus, when burning crude oil, the steam supply does not provide a decrease in the flame temperature, as it is observed when burning diesel fuel in the original burner [51]. In order to exclude a possible effect of the burner design on the combustion process, similar to the operational parameters of [51], combustion of diesel fuel was studied in a modernized burner at different steam and fuel-flow rates. The results on NO_x contents in the modernized and original burners are compared in fig. 9. It is seen that when diesel fuel is burned in both burners, an increase in the steam concentration leads to a decrease in nitrogen oxides, *i. e.* the burner design does not affect $\{NO_x\}$ behavior.

It can be assumed that the process of crude oil burning occurs in a different way: with increasing steam flow rate, the flame velocity increases and the flame temperature rises due to an increase in the completeness of combustion of heavy oil fractions. In the studied range of operating parameters, a change in the maximum temperature reaches 170 °C, and its maximum value is 1470 °C, fig. 8. In the regimes with the maximum completeness of fuel combustion, the content of NO_x is $\{NO_x\}$ < 225 mg/kWh, which corresponds to class 1 of the current standard EN 267 ($\{NO_x\} \leq$ 250 mg/kWh) [53]. At that, the [CO] values are minimal within the measurement accuracy of the gas analyzer, ±2 ppm. Thus, the results indicate the high environmental friendliness of the technology of crude oil combustion when being sprayed by a jet of superheated steam.

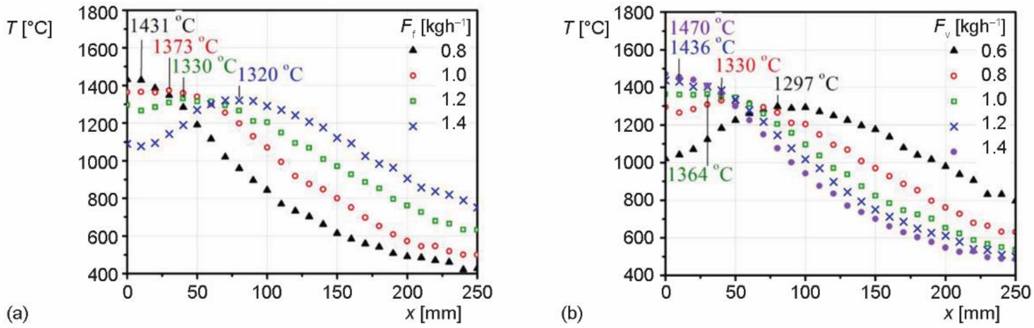

Figure 8. Time-average temperature in the external flame of the burner along the vertical axis (T_s = 260±10 °C) at crude oil combustion: (a) F_v = 0.8 kg/h at various F_f; (b) F_f = 1.2 kg/h at various F_v

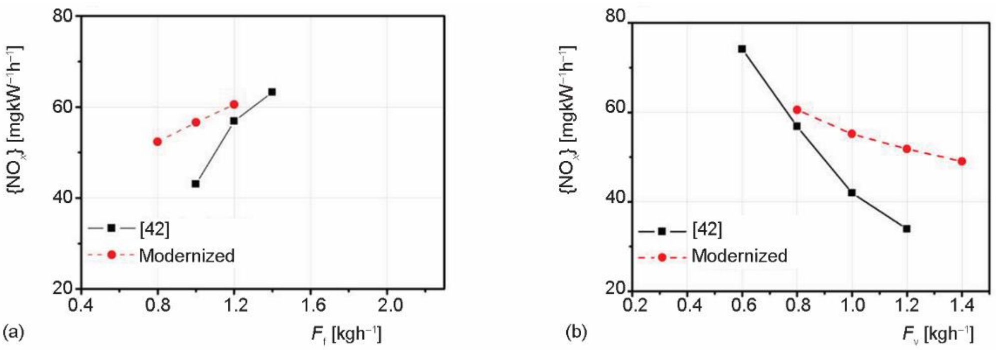

Figure 9. Concentration of NO_x in the products of diesel fuel combustion (T_s = 260±10 °C): (a) F_v = 0.8 kg/h; (b) F_f = 1.2 kg/h

The content of SO_2 in the combustion products, fig. 10, was also converted to milligrams per unit of heat in the equilibrium combustion products. It can be seen that with an increase in fuel-flow rate there is an increase in {SO_2}, fig. 10(a), and with an increase in steam flow rate, we observed a decrease in {SO_2}, fig. 10(b). In fig. 10, the dashed line shows the maximum value of {SO_2}, which corresponds to the complete conversion of sulfur contained in oil, tab. 2, into sulfur dioxide. The highest values of {SO_2} are achieved in Region III. 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.

A comparison of results in figs. 7 and 10 shows that the ratio of {NO_x} to {SO_2} in the combustion products is ~ 1:3. The concentration ratio of nitrogen, N, and sulfur, S, in the composition of oil is approximately the same, tab. 2. This suggests that high concentrations of NO_x at oil combustion in comparison with diesel fuel [51] can be explained by the presence of fuel nitrogen.

As a rule, industrial burners on heavy oil have an initial power of 200 kW and higher because complete combustion of fuel requires a large volume of the combustion chamber. In this regard, it is not possible to compare the results with analogues. Thus, the ensured possibility of crude oil burning in low-power burners is another important technical result, which allows designing burners for heat supply of small objects with the use of substandard fuel.

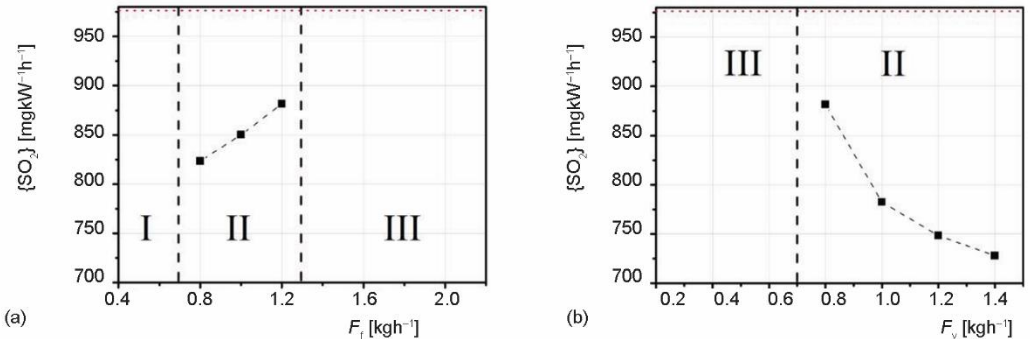

Figure 10. The {SO_2} in the products of crude oil combustion (T_s = 260±10 °C): (a) F_v = 0.8 kg/h; (b) F_f = 1.2 kg/h

Conclusions

The process of crude oil combustion by spraying it with a jet of superheated steam in a new atmospheric burner is first experimentally investigated in the work presented. An important practical problem of efficient dispersion of contaminated fuel and waste, eliminating the problem of coking nozzles and clogging of fuel channels, has been solved. To increase the efficient burning of heavy fuels, a principle of staged combustion is used, which allows an increase in the degree of flow circulation and, accordingly, completeness of fuel combustion. At the same time, steam supplying to the combustion zone allows the reduction of toxic emissions of NO_x and CO.

The most complete oil burning (~44 MJ/kg) is achieved in the entire range of stable burner operation with an air excess coefficient $\alpha \sim 1.0\text{-}1.85$. In these regimes, the content of nitrogen oxides and carbon monoxides corresponds to class 1 of EN 267 standard: [NO_x] < 180 ppm, [CO] < 2 ppm.

The proposed combustion method allows energy-efficient and environmentally friendly crude oil burning in the low-power burners (~15 kW). Such devices can be used for the cleaner elimination of liquid hydrocarbon waste with the receipt of thermal energy.

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Nomenclature

F_f – mass flow rate of fuel, [kgs^{-1}]
F_v, F_a – mass flow rate of atomizing gas (steam/air), [kgs^{-1}]
P – gas (steam/air) pressure in the heater, [Pa]
q – heat generation, [Jkg^{-1}]
T – local time average flame temperature, [°C]
T_s – initial atomizing gas (steam/air) temperature, [°C]
[X] – volumetric concentration of substance X in the composition of the combustion products, [vol.%]/[ppm]

{X} – mass concentration of substance X in the composition of the combustion products per unit of produced heat, [mgkW^{-1}h^{-1}]
W – power, [kW]

Greek symbol

α – excess air ratio, [–]

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