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Experimental Study of Kerosene Combustion Characteristics in a Jet of Superheated Steam with a Controlled Air Excess

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Abstract

The use of steam injection has a notable impact on reducing the presence of harmful elements in combustion products. This method promises to mitigate the environmental impact of heat and electricity generation facilities and transportation systems, especially in remote areas where combustion systems are essential. This study examined the effect of excess air ratio on the thermal and environmental properties of jet fuel combustion using superheated steam in a gas generation chamber using a laboratory burner apparatus. Measurements of intermediate and final combustion products, flame temperature and visual documentation of combustion were carried out. The findings indicate that optimal levels of carbon oxide and nitrogen oxides content in combustion by-products are achieved with superheated steam injection at an excess air ratio of approximately 0.2, meeting the strict requirements of the European standard for liquid fuel burners, EN 267. To maximize the efficiency of combustion during steam injection, a criterion for the minimum required air supply to the gas generation chamber was introduced.

Keywords: Low-emission burner; Atomization by superheated steam jet; Gasification; Excess air ratio.
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1. Introduction

The one of the main directions of scientific and technological development in modern society is reducing the anthropogenic impact on the environment.[1,2] The solution to this problem may be the transition to environmentally friendly energy sources, such as renewable energy. Replacement of internal combustion engines with emission-free devices, such as electric car motors,[3–5] is also a solution. However, modern technologies allow autonomous generation of heat and electric power, including those in transport systems, allow their application only locally, at short distances from centralized generation systems.[6] Therefore, in the near future, the trend of using traditional energy carriers to provide heat and power generation, as well as in transportation systems, at remote locations, including those in the far north or south, the Arctic or Antarctica, will continue.[7] Liquid hydrocarbon fuels like gasoline, kerosene, *etc*., have high energy density and are stable under normal conditions, and do not have high requirements for transportation and storage conditions. They have a wide range of practical applications in various power plants and devices. However, the combustion of these fuels produces harmful products that negatively affect the environment and human health.[8] The incomplete transition to environmentally friendly technologies, as well as the ever-increasing demand for energy and growing environmental concerns call for the further development and improvement of fuel systems with high efficiency and low emissions.

Nitrogen oxides,[9,10] are considered one of the most significant harmful substances produced during combustion. They are created through the oxidation of nitrogen present in the air during the burning process. Although nitrogen itself does not participate in combustion, the formation of NOx is greatly influenced by pressure and temperature, with their levels increasing exponentially as these parameters rise. The primary oxides formed are NO and NO2, with NO being the predominant one. NOx is toxic and contributes to the creation of chemical smog, as well as exacerbating ozone depletion.[11] The following approaches are considered to be available for their reduction.[9,12,13] Each of them allows us to achieve a certain level of NOx emission decrease: rich-burn, quick-quench, lean-burn (RQL),[14,15] lean premixed combustion

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(LPM),[16] the use of catalysts,[17] and also diluent application.[18,19]

Methods of lowering the nitrogen oxide production during the combustion process have both advantages and disadvantages. For example, the use of RQL strongly depends on the quality of mixing at different stages of the burner.[20,21] Uneven mixing of air and fuel can lead to areas of localized overheating, resulting in the formation of thermal nitrogen oxides. A quality mixing process ensures low combustion temperatures, which prevents the formation of thermal NOx, but can result in high underburning and the formation of unburned hydrocarbons (UHC) and CO.[22] One drawback of the staged system is that the combustion air temperature in all stages is limited to the temperature at the compressor outlet, leading to a low lean limit. Moreover, during low power operation, the lower temperature of the second stage can cool down the combustion in the first stage, resulting in higher levels of CO and UHC.[22] LPM combustion is widely used in gas engines.[23] It is also accepted that the concept can be extended to liquid fuels,[24] which are more common for use in remote locations. However, before mixing, the fuel must first be fully vaporized and then burned in the combustion chamber, which complicates the operation of the plant. In addition, combustion at LPM tends to be self-igniting due to the long time periods required for the vaporization and mixing of fuel and air.[22] At high temperatures at the combustion chamber inlet, conditions of high power can cause the mixture to ignite before it reaches the combustion zone. The potential for emission control with catalytic combustion at high temperatures is also limited because such systems have a finite operating life, and the higher the level of NOx emissions entering the catalytic system, the shorter the operating time of such systems.[25] Therefore, it is advisable to use them in combination with previous methods to reduce the amount of nitrogen oxides input to the catalyst. Hence, in the catalytic combustion approach, the significant problems to be overcome are satisfactory catalyst service limits and reliability under the harsh and varied operating conditions predominant in the combustion chamber. Since formation of NOx is currently largely dependent on combustion temperature, introducing a heat absorber to lower the combustion temperature could significantly reduce the amount of NOx produced during combustion. The approach of using various diluents is based on this principle. The dilution method has great potential for use in practical applications, such as electrical discharge machine (EDM) and compression ignition engines, and is considered to be an effective method of reducing combustion temperature and consequently NOx emissions. Carbon dioxide,[18] nitrogen,[19] water,[26] *etc*. can be used as diluents. These substances have different physical and chemical properties, so there may be noticeable differences in combustion characteristics when the mixture is diluted. Water is an effective diluent due to its high specific heat capacity.[27] Although water injection can significantly reduce NOx content, it has a number of disadvantages, such as water treatment costs, danger of device elements corrosion. At the same time, water injection is the most effective and easy to implement and use means of substantially suppressing NOx emissions, especially for liquid-fuelled plants.[28,29] Thus, when using liquid fuels for NOx control in low-temperature combustion mode, there are a number of atomization, vaporization and mixing peculiarities associated with high ignition temperature and long ignition delay.[30] Consequently, low emission devices require reliable ignition, flame stabilization and efficient combustion with limited duration and residence time.[31]

Steam injection has a similar effect to water in reducing NOx emissions,[32] so it is possible to use it not only as a diluent but also as a liquid fuel atomizer, which would provide efficient atomization and vaporization due to the direct contact of the fuel with the hot gas medium. Such a method of fuel atomization by steam jet,[33] where the fuel is fed directly into a high-speed gas jet, is proposed in Institute of Thermophysics of Siberian Branch of Russian Academy of Sciences (IT SB RAS). In this case, the use of steam allows one to perform the partial gasification of fuel in the presence of a mixing zone and gas generation, which ensures complete combustion of fuel with a significant reduction of NOx.[34] Previous studies were carried out by the authors on the combustion of diesel fuel atomized by superheated steam with controlled excess air in the gas generation chamber.[35] Reduced air supply with steam atomization of fuel has been shown to reduce NOx emissions by 70% at high combustion completeness without the use of additional systems.

As a continuation of previous studies, the present work investigates the combustion characteristics of another widely used liquid fuel, kerosene (Jet A), which differs from diesel fuel in terms of its physical properties and makes it impossible to predict the effect of steam influence on the combustion process characteristics. In Ref. [36] the modes and ratios of steam/fuel were shown for combustion of jet fuel on an atmospheric burner to provide low-pollutant emissions. However, air intake into the gas generation chamber was not controlled, so it was not possible to determine to what extent fuel gasification occurs in the area where it mixes with steam and evaporates. Therefore, the purpose of this work is to obtain experimental dependencies of the environmental indicators of the combustion of Jet A as a flammable liquid fuel during atomization by steam jets and its stay in the mixing zone, and the generation of gas at different air supplies. The data obtained will be used to create low-emission burners for liquid fuels intended for power plants in remote areas.

2. Experimental setup and measurement methods

The research focused on investigating the combustion characteristics of jet fuel in a jet of superheated steam with controlled excess air using a spray burner with adjustable air supply to the gas generation chamber (Fig. 1). This burner employs a technique for dispersing and burning liquid fuel, where the high-speed steam jet interacts with the fuel, leading

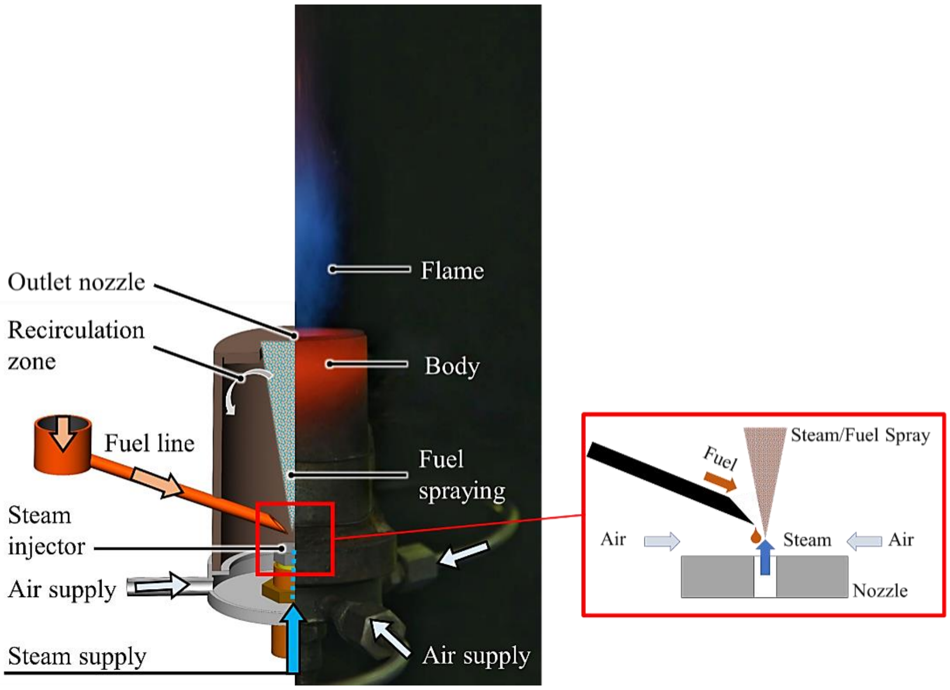


Fig. 1 Schematic diagram of a burner with fuel atomization (orange arrow) by a jet of superheated steam (blue arrow) with controlled air flow (gray arrows) into the gas generation chamber.

to its evaporation, partial steam gasification of thermal decomposition products, and incomplete combustion of the fuel in the burner device's gas generation chamber. Further details about the device can be found in the referenced work.[35]

The study investigated the impact of the excess air ratio in the burner gas generation chamber on the external flame temperature, the composition of intermediate and final combustion products, and the degree of liquid fuel combustion completeness using the device. The research was conducted on an experimental setup designed for studying the soot-steam combustion mode of liquid hydrocarbons, which is part of the specialized scientific facility "Large-scale thermo-hydrodynamic stand for analyzing the thermal and gas-dynamic characteristics of power units". The setup comprises the burner unit, a water supply system, an electric steam generator, and an air supply system (refer to Fig. 2). Steam is heated and superheated by a laboratory electric steam generator with a capacity of up to 2 kW, while water is

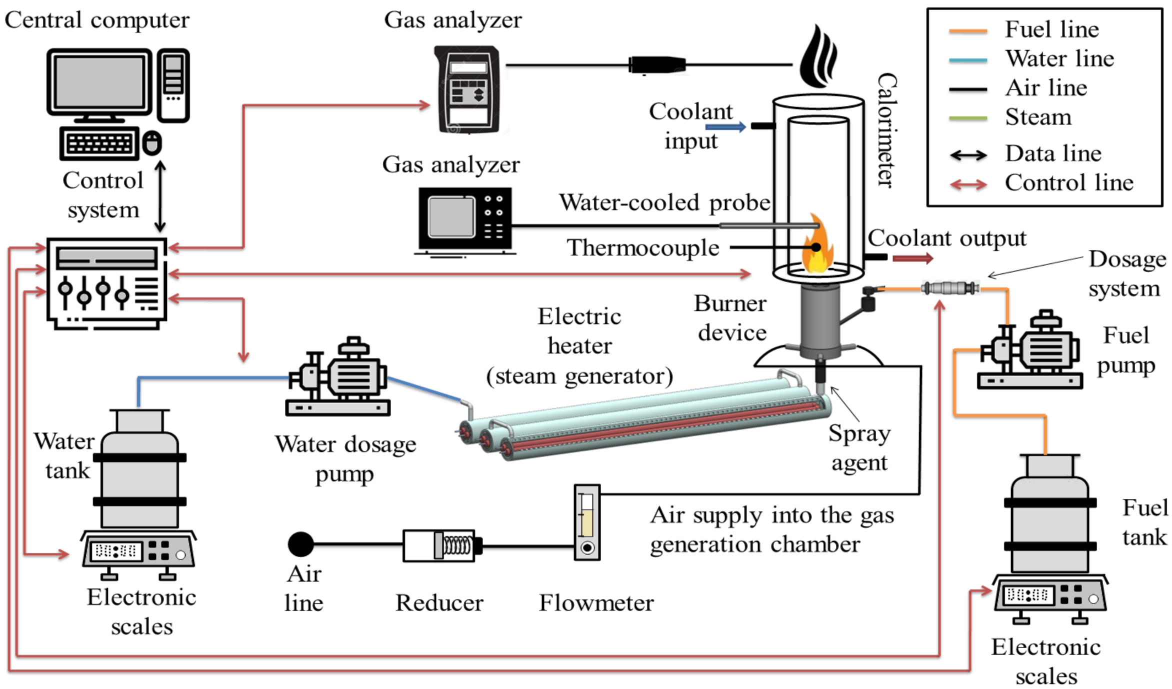


Fig. 2 Schematic diagram of the experimental stand for investigation of combustion characteristics of liquid fuel atomized by a steam jet.

delivered to the steam generator through a pumping system (flow rate up to 1.5 kg/h, with a supply stability of 2%) and monitored by scales. Liquid fuel is supplied via a pump (flow rate up to 2 l/min), with the mass flow rate controlled by a fuel valve (0.1-4 kg/h, with a supply stability of 2%). The excess air introduced to the gas generation chamber from the central compressed air line through a reducer was adjusted using a Bronkhorst MASS-VIEW mass flow meter. Further details about the setup can be found in the referenced paper.[35]

Measurement of intermediate combustion products in the flame was carried out on the stand using a Test-1 gas analyzer. Components to be measured: CO (0-10 % об.), H_2 (0-40 % об.), C_nH_m (0-20 % об.), CO_2 (0-20 % об.), O_2 (0-21 % об.), NO (0-1000 ppm). To collect gas samples from the flame, a water-cooled probe with an inner channel diameter of 2 mm was used. The combustion products were cooled to room temperature to halt the ongoing combustion processes and to accurately determine the gas composition of intermediate components within the flame. Gas sampling was conducted along the burner axis with a 20 mm step at a distance of 240 mm from the outlet nozzle. Each sampling point had a duration of 90 seconds, with a sampling frequency of 1 Hz.

The time-averaged temperature within the flame was measured using a Pt-Rh/Pt-Rh thermocouple positioned along the burner axis with a 10 mm step at a distance of 200 mm from the base of the flame. Each measurement point lasted 30 seconds during the experiment (with a sensor thermal inertia of 5 seconds), with data acquisition occurring at a frequency of 10 Hz for 20 seconds and a 10-second delay at each point. Additionally, radiation losses from the thermocouple surface in the high-temperature flow were considered in the measurements.

The concentration of substances in the combustion products was determined using a Testo 350 gas analyzer. The components to be measured: O_2 (0-25 об. %), NO (0-300 ppm), NO_2 (0-500 ppm), CO (0-500 ppm) и CO_2 (0-50 об. %). Sampling was performed at the outlet of the flow calorimeter, where the gases have a temperature close to the room. Measurements for each mode lasted 5 min at a frequency of 1 Hz and were averaged.

3. Results and discussion

The concentrations of intermediate and final products of the fuel combustion, flame temperature were measured. The gross formula of the jet fuel under study is $C_{14}H_{27}N_{0.038}$. The parameters of the investigated modes are presented in Table 1. Steam and fuel flow rates were selected for the modes based on the results of operation for the atmospheric burner with natural air supply to the gas generation chamber.[36]

Table 2 displays images of the burner flame captured at various air flow rates supplied to the gas generation chamber. The flame was photographed using a Nikon D780 camera with settings including a shutter speed of 1/30 s, ISO-200, and an aperture f/4. The flame exhibited a characteristic shape for diffusion combustion in the different modes. It appeared predominantly blue, with yellow-orange regions becoming more prominent at higher fuel flow rates (1.4 kg/h). As the air flow rate increased, the visible length of the flame decreased from 300 to 250 mm for modes with a kerosene flow rate of 1.4 kg/h, and from 150 to 100 mm for a fuel flow rate of 1.0 kg/h. When maintaining equal steam flow rates of 0.8 kg/h and air flow rates into the gas generation chamber, a reduction in fuel consumption resulted in a shorter visible flame length, with the flame color shifting to a blue hue without yellow-orange areas.

The time-averaged flame temperature profiles along the vertical axis of the burner are shown in Fig. 3.

In modes with a fuel flow rate of 1.4 kg/h, the flame temperature peaks at approximately 130 mm from the burner nozzle at an air flow rate of 3.3 kg/h. As the air flow rate into the gas generation chamber increases, the temperature peak shifts closer to the base of the flame, reaching around 60 mm at an air flow rate of 15 kg/h, accompanied by a noticeable decrease in visible flame length. The maximum temperature values are consistent within the margin of error, ranging between 1750-1800 °C. Additionally, an increase in air supply results in a rise in temperature at the nozzle outlet, from 900 to 1450 °C.

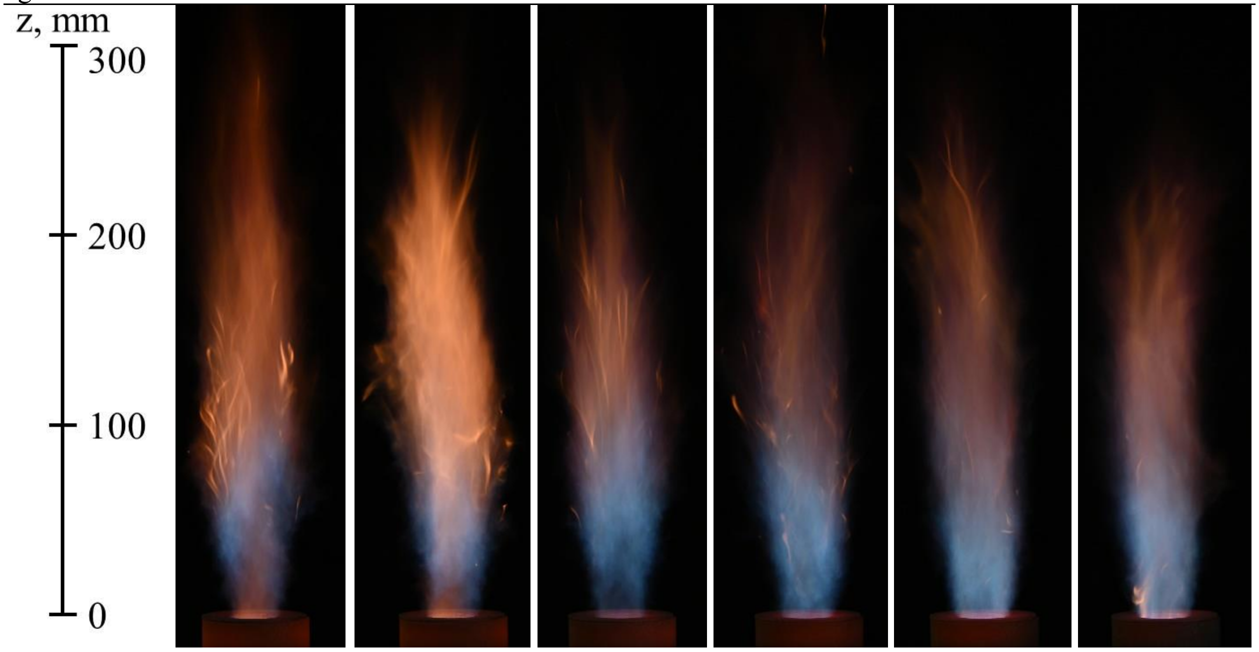
At a lower fuel flow rate of 1.0 kg/h, a similar trend is observed when adjusting the air supply to the gas generation chamber. With higher air flow rates, the temperature peak shifts closer to the base of the burner flame, moving from approximately 70 mm to 50 mm from the nozzle edge, while the visible flame length decreases. The peak temperature measurements are comparable within the error range, ranging between 1500-1550 °C, which is around 250 °C lower than in high fuel consumption modes. The positioning of the temperature peaks at varying distances from the burner nozzle aligns with the visual observations of the diffusion flame type in Table 2, indicating that the primary combustion processes occur as external air from the environment mixes with the exiting mixture from the gas generation chamber. The

Table 1. The parameters of the investigated modes.

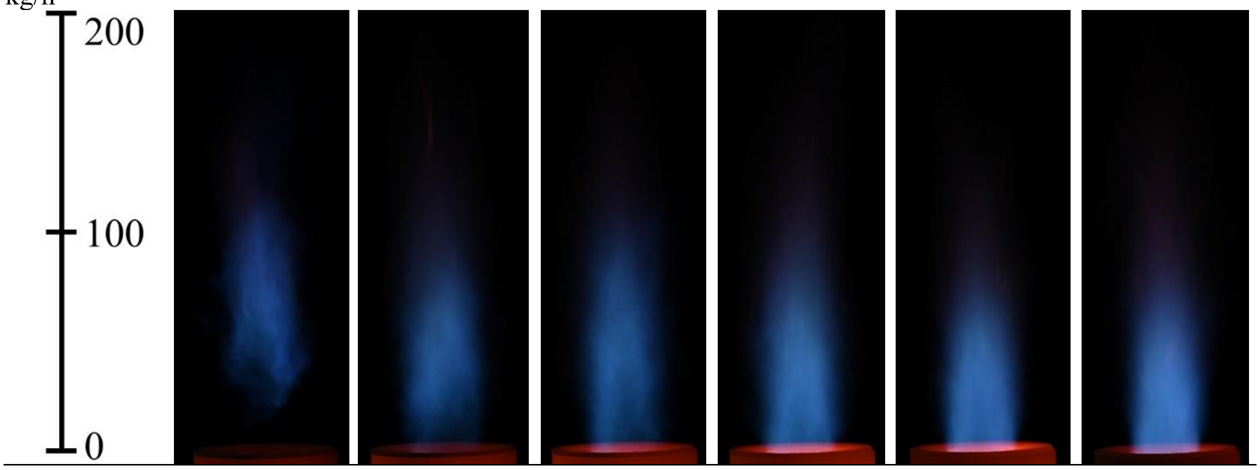
Parameters	Modes											
Air flow rate into the gas generation chamber, kg/h	3.3	4.5	7	9.5	12	15	2.75	4.5	7	9.5	12	14.3
Equivalence air/fuel ratio	1.20	1.22	1.19	1.22	1.33	1.53	1.20	1.21	1.27	1.39	1.56	1.71
Fuel flow rate, kg/h	1.4						1.0					
Steam flow rate, kg/h	0.8						0.8					
Steam temperature, °C	250						250					

Table 2. Characteristic flame photos for different mode parameters.

Kerosene flow rate 1.4 kg/h, steam flow rate 0.8 kg/h						
Air flow rate, kg/h	3.3	4.5	7	9.5	12	15



Kerosene flow rate 1.0 kg/h, steam flow rate 0.8 kg/h						
Air flow rate, kg/h	2.75	4.5	7	9.5	12	14.3



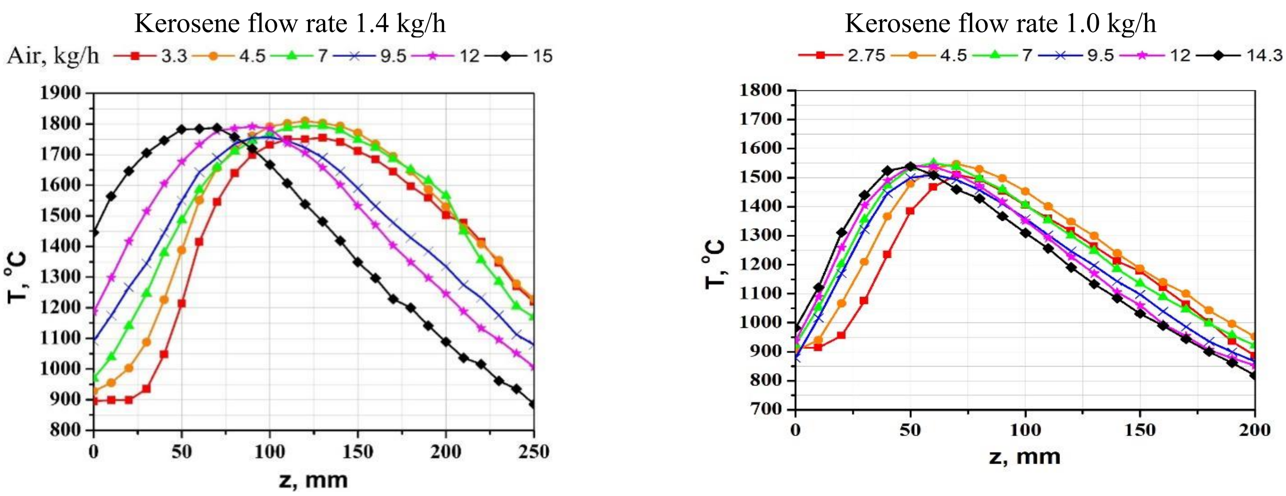
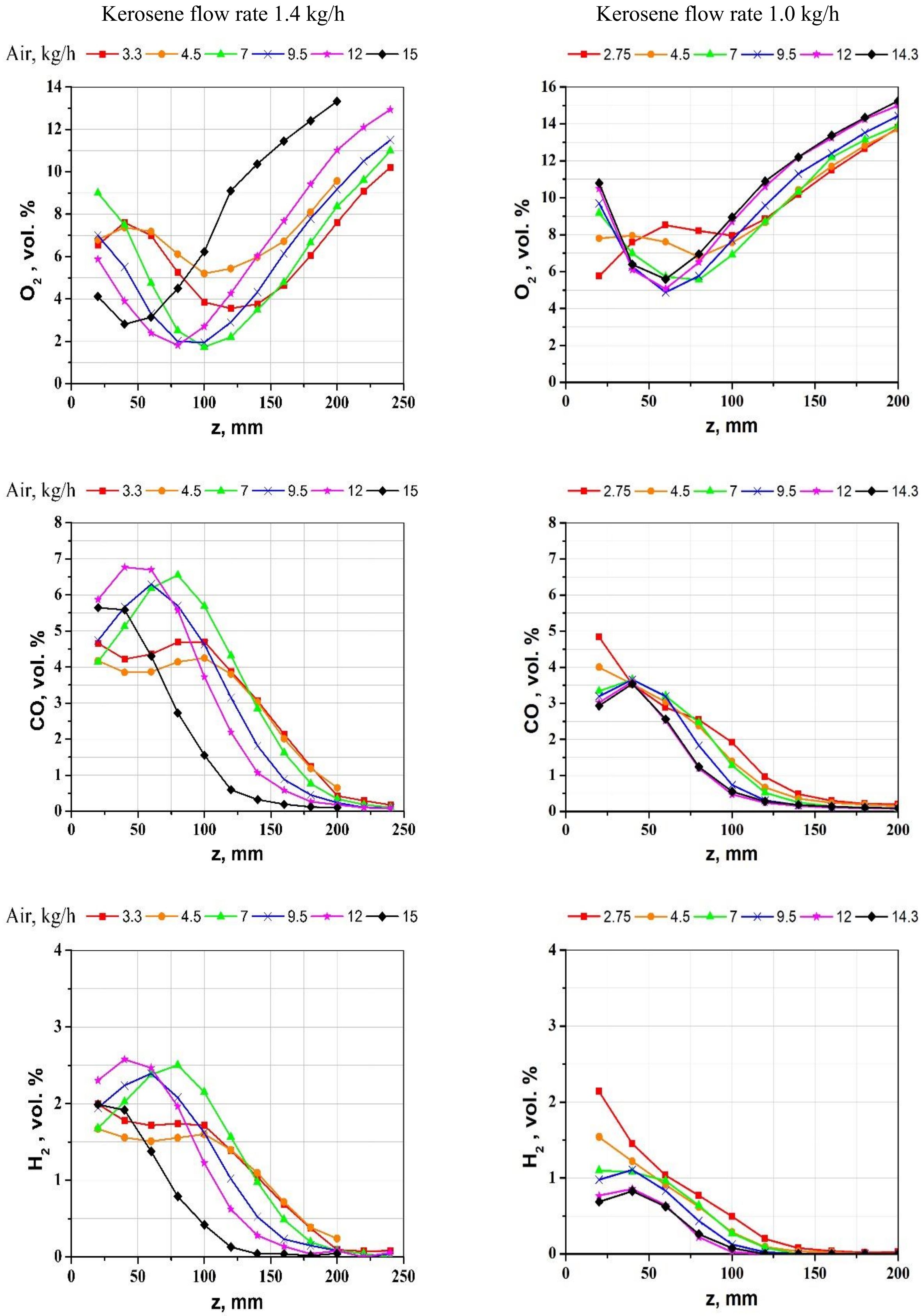


Fig. 3 Dependence of the average flame temperature along the vertical axis of the burner.

temperature at the nozzle outlet reaches 900 ℃ at the lowest air flow rate into the combustion chamber, likely representing the minimum temperature required to sustain mixture self-ignition due to the formation of a recirculation zone beneath the nozzle.

The concentration profiles of the fuel combustion intermediate components along the vertical axis of the burner are shown in Fig. 4.



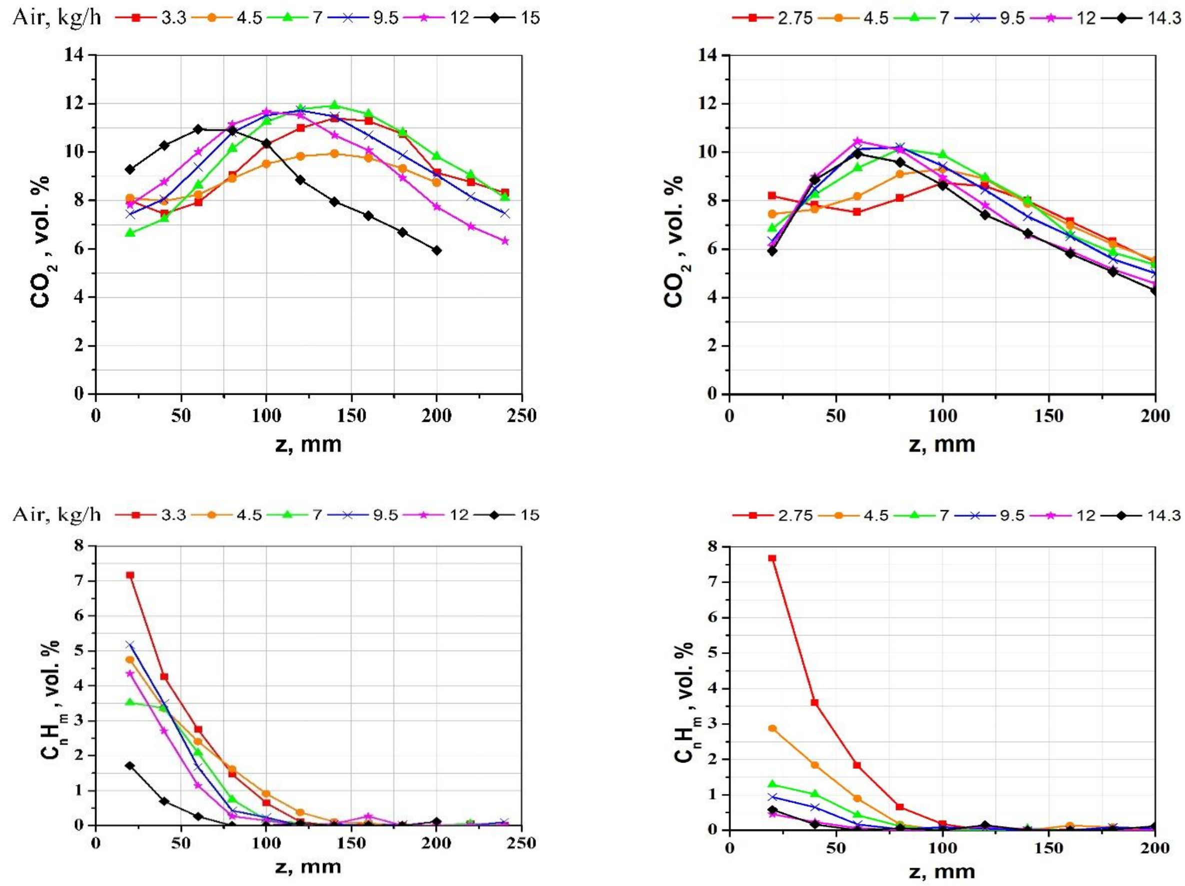


Fig. 4 Concentration profiles of gas components in the flame along the vertical axis of the burner device.

The profiles obtained show that the minimum of O_2 and maximums of CO, CO_2, H_2 shift closer to the base of the flame as the air flow rate into the gas generation chamber increases, indicating a faster afterburning of the mixture after leaving the burner. This is also confirmed by the decrease of C_nH_m concentration at nozzle exit from 7.2 to 1.7 vol% for a fuel flow rate of 1.4 kg/h (from 7.6 to 0.5 vol% for a fuel flow rate of 1.0 kg/h) while increasing the air flow rate from 3.3 (or 2.75) to 15 (or 14.3) kg/h. Faster afterburning is most likely due to the larger amount of oxidizer in the gas generation chamber, thereby burning more fuel inside the device so there is a tendency towards direct oxidation of fuel rather than its gasification. Thus, for modes with higher fuel flow rate, this effect is more evident than for modes with lower fuel flow rate, where the effect is noticeable at air flow rate less than 9.5 kg/h. At fuel flow rate of 1.0 kg/h and air flow rate from 9.5 kg/h to 14.3 kg/h, the maximums of CO, CO_2, H_2 and minimum of O_2 are at the same distance, and also the concentrations of gas components are close in values along the vertical axis, which indicates a weak dependence of the processes on the air flow rate in this range of regime parameters, which is also indicated by the coincidence of temperature profiles within the errors for these 3 modes.

Figure 5 shows the dependence of the concentrations of harmful substances in the combustion products on the supplied air.

For modes with a fuel flow rate of 1.4 kg/h (left diagram), there is a weak growth in the concentration of both carbon monoxide and nitrogen oxides in the combustion products when the air flow rate supplied to the gas generation chamber is increased. When the air flow rate is reduced from 14.3 kg/h to 2.75 kg/h, there is a decrease of CO by 70% and NO by 20%. For modes with fuel consumption of 1.0 kg/h (right diagram), such a decrease is observed when an air flow rate is reduced to less than 9.5. At higher flow rates, a sharp increase in carbon monoxide is observed due to the transition to the pulsation behavior of the flame, shown for the atmospheric device in the paper.[36] The total concentration of CO and NO is minimal for the 4.5 kg/h air supply mode, which is equivalent to an air excess inside the gas generation chamber of 0.22 and 0.31 for the 1.4 kg/h and 1.0 kg/h modes, respectively. At the same time, for these modes, the emission concentrations of toxic substances satisfy the strictest class of the European standard for liquid fuel burners EN 267 (CO < 60 mg/kWh, NOx < 120 mg/kWh).

The data obtained indicates that the air supply to the gas generation chamber influences the extent of fuel oxidation within the device. Specifically, an increase in air flow rate is likely to shift fuel reactions from gasification towards oxidation. To confirm this, the luminosity intensity of the flame along the vertical axis of the burner was assessed based on photographs captured in the visible spectrum (see Fig. 6).

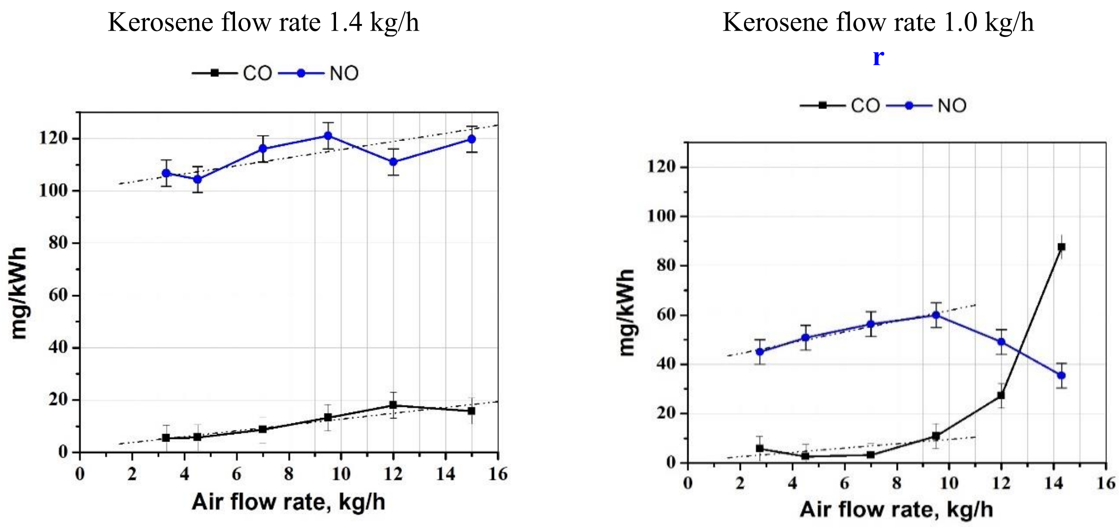


Fig. 5 Dependence of NO and CO concentration in combustion products on the air flow rate into the gas generation chamber.

Flame luminosity profiles were plotted in ImageJ program using the Plot profile function, which gives Gray value along the selected segment. The vertical axis of the burner from the edge of the nozzle to a distance of 200 mm upstream was chosen as the segment. Also, for plotting the Gray value from white (0% gray) to black (100% gray) was converted to Intensity in percent (0 to 100%).

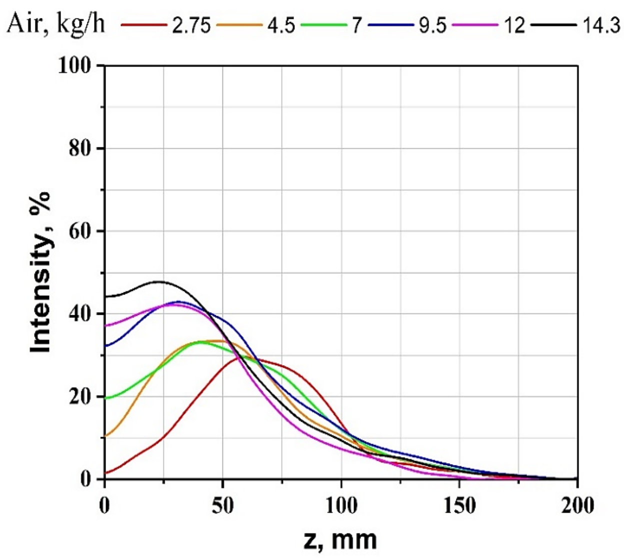


Fig. 6 Flame luminosity profiles for a fuel flow rate of 1.0 kg/h.

It can be seen from the figure that with increasing air flow rate there is a growth of luminosity intensity, which may indicate additional formation of substances radiating in the visible spectrum, such as solid carbon particles, which is caused by a decrease in the level of steam gasification of the fuel and a shift towards its oxidation inside the device.

This shift can be estimated from the ratio of the amount of heat required for the gasification reaction to occur, in the example of $C + H_2O = CO + H_2$ - 131.3 kJ/mol,[37] to the total amount of heat produced by the oxidation of the fuel by the air entering the gas generation chamber. For the estimation we use the assumptions of adiabatic process, that the heat remains in the system and is not radiated by the burner surfaces. Gasification is assumed to occur at a temperature of 900°C, according to the temperature at the outlet of the burner for modes with low air flow rate supplied to the device (Fig. 3). The heat consumed for the gasification process is calculated by the formula:

$$Q_{gas} = \Delta H_f^0 \, F_{gas}/M, \quad (1)$$

where ΔH_f^0 = 131.3 kJ/mol is the standard enthalpy of the gasification reaction; F_{gas} is the mass of steam involved in gasification per hour (not all of the supplied steam is involved in gasification, the mass of steam involved in gasification calculated according to the flow rates of steam, air and experimentally obtained concentrations of gas components at the nozzle outlet), kg/h; M = 0.018 kg/mol is the molar mass of steam. The heat spent on heating steam, air and fuel to the temperature at the nozzle outlet is estimated by the formula:

$$Q_{heat} = \sum_i C_i F_i \left(T_{out} - T_{in_i}\right), \quad (2)$$

where index i corresponds to steam, air and fuel; C_i is the heat capacity of the i-th substance, kJ/kg·K; F_i is the flow rate of the i-th substance, kg/h; T_{out} is the outlet temperature measured experimentally, K; T_{in_i} is the inlet temperature of the i-th substance, K (for steam T_{in} = 353 K, for air and fuel T_{in} = 300 K). Estimation of heat released during conversion of a part of fuel into CO, CO_2 and H_2O is made by the formula:

$$Q_{tr} = \sum_i \Delta H_{f\_i}^0 \, F_i/M_i, \quad (3)$$

where index i corresponds to substances CO, CO_2 and H_2O; $\Delta H_{f\_i}^0$ is the standard enthalpy of formation of the i-th substance, kJ/mol; F_i is the flow rate of the i-th substance (calculated according to the flow rates of steam, air and experimentally obtained concentrations of gas components at the nozzle outlet), kg/h; M_i is the molar mass of the i-th substance, kg/mol.

The results obtained from the evaluation are shown in Table 3.

It is shown from the table that the minimum possible modes in terms of air flow rate supplied to the gas generation

Table 3. Estimation of the amount of heat required for the gasification reaction for the investigated modes.

Mode	Kerosene flow rate 1 kg/h						Kerosene flow rate 1.4 kg/h					
Air flow rate, kg/h	2.75	4.5	7	9.5	12	14.3	3.3	4.5	7	9.5	12	15
Equivalence air/fuel ratio	1.20	1.21	1.27	1.39	1.56	1.71	1.20	1.22	1.19	1.22	1.33	1.53
Heat for gasification, Q_{gas} (1), MJ/h	1.56	1.33	1.27	1.11	1.62	1.81	1.87	1.75	2.32	3.15	4.55	4.14
Heat to warm up to the outlet temperature, Q_{heat} (2), MJ/h	6.49	7.93	10.36	11.95	15.05	17.99	7.86	9.24	12.02	16.25	20.59	29.48
Heat from conversion of part of the fuel, Q_{tr} (3), MJ/h	8.46	9.80	12.09	14.37	16.83	19.04	9.21	10.85	12.85	18.91	25.24	33.19

chamber correspond to the minimum level of heat going to warm up the supplied substances up to the temperature required for self-ignition of the mixture in the recirculation zone, and equal to ~ 900 °C. The heat received at transformation of a part of fuel into CO, CO2 and H2O is used for heating of substances and for gasification of products of incomplete oxidation of kerosene at involvement in the process of a part of superheated steam. Fig. 5 shows that in the area of minimum values of air flow rate, the best performance in terms of CO and NOx content in combustion products is achieved. Thus, when developing low-emission burner devices based on fuel atomization by a jet of superheated steam, by approximating the obtained mode characteristics of the burner device operation, it is possible to introduce the criterion of the minimum required amount of air supplied to the gas generation chamber $F_{\_in\_min}$ [kg/h] to ensure the best combustion performance:

$$F_{in\_min} = a + bF_{fuel} \quad (4)$$

where a = 1.375 kg/h, depends on the steam flow rate and jet velocity at the nozzle outlet, b = 1.375; both coefficients were found for the specific present burner design.

4. Conclusion

The study investigates how the excess air ratio within the gas generation chamber affects the thermal and environmental characteristics of kerosene (Jet A) combustion when it is atomized by a superheated steam jet. Experiments were conducted using a laboratory-scale burner device that atomizes liquid fuel by a superheated steam jet and allows for control of excess air ratio in the gas generation chamber.

In the study, the concentrations of intermediate and final products of fuel combustion were measured, as well as flame temperature and visual monitoring of flame parameters and the combustion process. Within the investigated range of operating parameters, low total concentrations of carbon monoxide and nitrogen oxides emissions were observed at an air flow rate of 4.3-6.5 kg/h, corresponding to an excess air ratio inside the device of 0.2-0.4. An increase in the air flow rate into the gas generation chamber caused an increase in CO concentration in the combustion products and a shift in the temperature peak towards the base of the flame along the vertical axis. The value of the temperature peak remained consistent within error margins when other parameters were held constant.

It has been shown that in the range of minimum values of air flow rate at the excess ratio of ~ 0.2 in the gas generation chamber the best indicators for CO and NOx content in the combustion products are achieved. These indicators satisfy the third class of the European standards for liquid fuel burners (EN 267) with CO < 60 mg/kWh and NOx < 120 mg/kWh. In this regard, a criterion of the minimum required air supply to the gas generation chamber was introduced, which corresponds to the minimum amount of heat required to warm up substances supplied to the necessary temperature for self-ignition in the recirculation zone under the nozzle. This criterion was determined for a particular burner design studied in the paper.

Therefore, the excess air ratio has a noticeable influence on the combustion processes and characteristics when using steam injection. Therefore, its control and appropriate choice are important in order to reduce the emission of toxic substances formed during the combustion of liquid hydrocarbon fuels. These results will be used to generalize dependencies and create predictive models for the effects of superheated steam addition on the combustion process of liquid fuel, which can be used for the development and creation of low-emission burners.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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