

COMBUSTION OF DIESEL FUEL SPRAYED WITH COLD OR HEATED AIR IN AN ATMOSPHERIC BURNER

by

**Mariia MUKHINA^a, Ivan SADKIN^{a,b}, Evgeniy SHADRIN^{a*},
and Evgeny KOPYEV^a**

^a Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia

^b Novosibirsk State Technical University, Novosibirsk, Russia

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In this work the combustion characteristics of liquid hydrocarbons when atomized by a high speed air jet were studied, using diesel fuel as an example. This approach to spraying liquid fuel in combustion processes has a number of advantages over traditional spraying: the ability to supply fuel with a low degree of purification, reducing the chance of coking of fuel equipment. Using an atmospheric burner device with natural air supply into the mixing chamber, the dependences of the composition of intermediate and final combustion products were studied, and the flame temperature was measured at various fuel flow rates and parameters of the atomizing air jet (flow rate, temperature). A comparison of the obtained characteristics was made for equivalent modes at different temperatures of the supplied atomizer. It was found that when heated air is used as a sprayer, higher flame temperatures are ensured, which ensures more complete fuel burnout and a decrease in CO concentration in the flue gases, but at the same time, a slight increase in NO_x was observed.

Key words: liquid hydrocarbons, fuel atomization, combustion, emission reduction

Introduction

In connection with the tightening of standards for the content of harmful substances in exhaust gases, research in the field of emission reduction technologies is relevant. Among the various emission control methods in modern combustion systems, dilution is widely used to reduce the peak combustion temperature and therefore, the NO_x concentration in the exhaust gas. Methods such as flue gas re-circulation [1], staged combustion systems [2], CO₂ dilution [3], MILD combustion [4], and others are widely used. This explains the interest in studying the influence of various diluents and dilution coefficients on the environmental and thermal characteristics of combustion [5].

In addition the type of diluent and dilution factor, the content of harmful substances in combustion products can also be affected by the temperature of the supply medium. In Papa-
giannakis [6] the effect of air intake preheating on the performance of a dual-fuel diesel engine is studied. This method, combined with the EGR method [7, 8], has been shown to increase engine efficiency (up to 5%) and reduce CO emissions (up to 10%). Thus, in Xu *et al.* [9] it was suggested that an increase in the initial temperature of the preliminary synthesis gas/air mixture

* Corresponding author, e-mail: evgen_zavita@mail.ru

leads to an increase in the laminar combustion rate and adiabatic flame temperature. In [10], the authors examined the effect of intake air temperature (40 °C and 60 °C) on the performance of a diesel engine. It has been shown that preheating the intake air can reduce CO and particulate matter emissions, but increases NO_x in the exhaust gases.

In IT SB RAS the method of combustion of liquid hydrocarbon fuel dispersed by a high speed jet of superheated steam [11], as a low emission combustion approach with a diluent, is researched. A distinctive feature of this method from traditional approaches is that it is based on the interaction of a high speed gas jet with a drop of fuel, which ensures high quality dispersion of various types of fuel [12] and can even be used for burning liquid combustible waste. The works also show that the use of superheated steam can significantly reduce the content of harmful emissions in combustion products compared to heated air and CO₂.

Thus, the use of superheated water steam allows for partial steam gasification when interacting with a fuel drop. In addition, it ensures a reduction in the concentration of NO_x in exhaust gases by up to 50% with high combustion efficiency of hydrocarbon fuels [13, 14]. In the works, this effect is associated with a decrease in the flame temperature, due to which the formation of *thermal* NO_x is reduced. However, previous studies have not studied the influence of atomizer parameters (type, temperature, flow rate, *etc.*) on liquid fuel combustion processes to identify the most effective diluent atomizer in terms of reducing CO and NO_x emissions.

In this work, a comparative study of the combustion characteristics of liquid fuel is carried out when it is dispersed by a high speed jet of compressed air at room temperature and heated air under equivalent conditions. The environmental and thermal performance of air atomization is compared with results obtained using superheated steam. For this purpose, the dependences of the composition of intermediate and final combustion products were obtained, the flame temperature was measured at various fuel flow rates and parameters of the atomizing air jet (flow rate, temperature), reduced to an equivalent value according to the criterion of the dynamic effect of the spray jet on the fuel flow.

The research results can be used when choosing the optimal sprayer for practical use in the national economy, taking into account the physical availability of a particular sprayer and the technical/technological difficulties associated with its use.

Experimental set-up

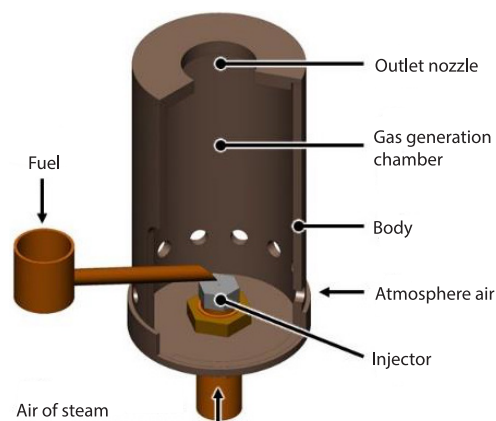


Figure 1. The scheme of an atmospheric burner device

For experimental studies, a laboratory sample of an atmospheric burner with a power of up to 20 kW was used, fig. 1. The main elements of the burner device are: base, body, outlet nozzle, spray nozzle (injector), fuel supply tube. In the lower part of the burner body there are openings for the natural flow of atmospheric air from the environment. In the burner, the fuel is atomized directly by a high speed air stream supplied from the nozzle. The resulting finely dispersed gas-droplet flow is ignited by an external burner. A detailed description of the device is given in [15].

The burner device was mounted on an open experimental stand, which has automated

systems for supplying and adjusting fuel and compressed air. The scheme of the experimental stand used in the work is presented in fig. 2.

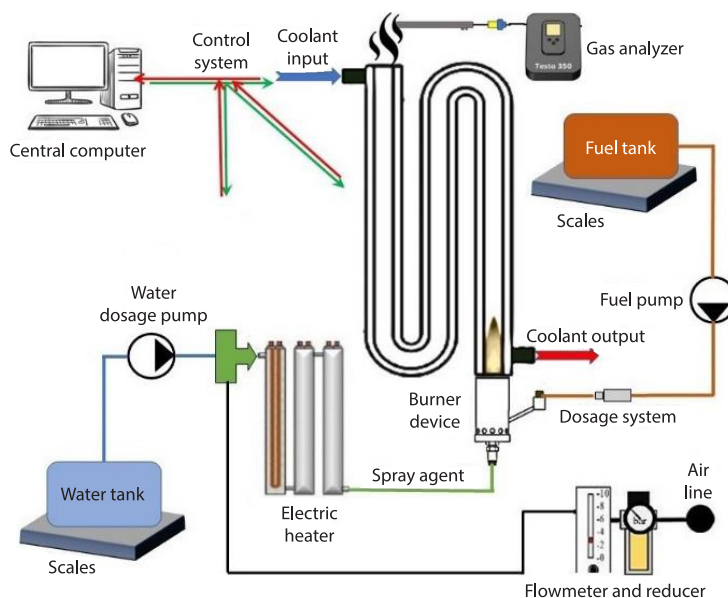


Figure 2. The scheme of an experimental stand

Flame temperature measurements were made using a type B thermocouple, which was moved within the flame using an automated co-ordinate-moving device. To carry out gas analysis of intermediate reaction products in the burner flame, a Test 1 gas analyzer (O_2 , CO_2 , CO , H_2 , C_nH_m , *etc.*) was used. The gas composition of the final products of diesel combustion was determined using a Testo 350 gas analyzer (O_2 , CO , NO_x , *etc.*). To determine the heat of combustion of fuel, a flow calorimeter was used, which is a *pipe-in-tube* design, the internal channel is for gas-flow, the external channel is for the coolant (water), flowing in the opposite direction, it serves to remove heat from the combustion products. The temperature measurement error did not exceed 5%. Measurement errors for Test 1 are CO abs. ± 0.2 %vol. with measured values from 0 to 5 %vol., rel. $\pm 5\%$ over 5-10 %vol., H_2 – rel. $\pm 5\%$, CH – abs. ± 0.2 %vol. with measured values from 0 to 5 %vol., rel. $\pm 5\%$ over 5-20 %vol., CO_2 – abs. ± 0.2 %vol. with measured values from 0 to 7 %vol., rel. $\pm 5\%$ over 7-20 %vol., O_2 – abs. ± 0.2 %vol. Measurement errors for Testo 350 are: NO_x – abs. ± 2 ppm with measured values from 0-39.9 ppm, rel. $\pm 5\%$ in the rest of the range. The error in determining the heat of combustion was 2.5%. The experimental set-up is described in more detail in [14].

Diesel fuel was used for research. Fuel atomization was carried out with cold compressed air (at room temperature $\sim 21^\circ C$) and heated to $250^\circ C$. The studies were carried out for the modes presented in tab. 1. The choice of modes is due to the fact that in work [15] when burning diesel fuel atomized with heated air for the specified parameters, a high completeness of fuel combustion and a low CO content in the combustion products were observed, tab. 1, Modes 4 -6). Modes 1-3 were selected from equivalence to Modes 4-6 according to the parameter of the dynamic impact of the spray jet, calculated according to [16]. The dynamic impact of the jet determines the amount of external air ejected from the environment. Thus, the selection of modes with the same value of this parameter guarantees the comparison of flames with the same excess air.

Table 1. Parameters of the studied modes

Mode	1	2	3	4	5	6
Atomizing medium temperature (air), [°C]	21			250		
Pressure, [atm]	6	7.5	8.9	5.7	7.5	8.6
Air-flow rate, [kg per hour]	1.05	1.33	1.57	0.81	1.07	1.24
Dynamic impact, [N]	0.146	0.193	0.234	0.149	0.207	0.245
Fuel consumption, [kg per hour]	1.2					

Results and discussion

Figure 3 shows photographs of the flame for modes where diesel fuel is sprayed with a stream of air at room temperature (Modes 1-3) and a stream of heated air $T = 250\text{ }^{\circ}\text{C}$ (Modes 4-6). When fuel is atomized with a stream of air at room temperature, more yellow-orange zones are observed in the flame than when burning diesel in a stream of heated air. Equivalent Modes 1 and 4, 2 and 5, 3 and 6 have a similar external flame size, which indirectly indicates the correct selection of modes according to the parameter of the dynamic effect of the spray jet. It can be seen that with increasing sprayer flow rate, the apparent length of the flame decreases both with a cold and heated sprayer, and its color becomes predominantly blue due to a greater degree of dilution with air ejected from the environment by the spray jet.

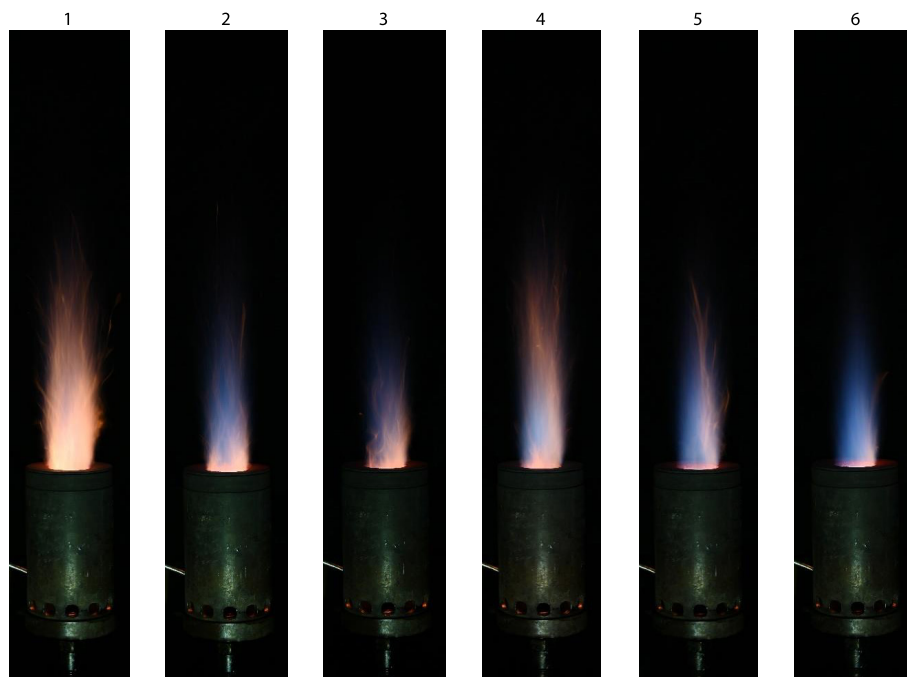


Figure 3. Photographs of the flame of the burner device, names of modes correspond to tab. 1

Figure 4 shows the flame temperature profiles along the vertical axis of the burner nozzle. The temperature profiles for the studied modes have a similar appearance. The maximum temperature is reached at a certain distance from the nozzle, which indicates that the fuel

burns out when leaving the burner device. As the sprayer flow rate increases, the maximum temperature decreases and moves upstream, which is most likely due to a greater dilution of the mixture with air ejected from the environment, which can be seen when moving to modes with a high dynamic impact number of 3 and 6, respectively for cold and heated air. At the same time, for air heating Modes 4-6, the flame temperature is higher ($\sim 100^\circ$) than for Modes 1-3, which is probably due to the difference in the initial parameters of the atomizer temperature, for example, an additional decrease in temperature can occur due to heat consumption for evaporation of fuel and heating of the atomizer in the case of atomization with cold air, from which one can expect a decrease in the probability of NO formation by the thermal mechanism, thereby reducing the content of nitrogen oxides in the final combustion products.

Figure 5 shows the concentration profiles of various gas components along the vertical axis of the burner nozzle. The component profiles have a similar appearance, but different levels of substances. These results may be due to the fact that jet parameters with equal dynamic impact were selected for comparison. Thus, at different air temperatures it is necessary to set different flow rates for equivalent modes. Despite this, it can be qualitatively noted that the maximum values for CO₂ and CO, and the minimum values for O₂ with heated air are closer to the base of the external flame, which indicates a slightly earlier ignition of the fuel, which is probably also associated with higher average temperature values in the torch for Modes 4-6, fig. 4. Also, it should be noted that the volumetric concentration of intermediate combustion products such as H₂ and CO, C_nH_m for heated air is much higher than for cold air, which may indicate preliminary dissociation of the fuel (pyrolysis) upon interaction with a hotter atomizer, from which one can expect more low concentrations of CO and particulate matter in the final combustion products.

Table 2 presents the results of measuring the content of CO and NO_x in the final combustion products, as well as the calculated specific heat of combustion of diesel fuel in the burner device when it is atomized with air of varying degrees of heating for Modes 3 and 6, as well as the equivalent mode when atomizing fuel with superheated water vapor [15].

Table 2. Thermal indicators of the burner device

	Specific heat, [MJkg ⁻¹]	CO [mg per kWh]	NO _x [mg per kWh]	Class according to EN 267
3 – Cold air	43.6	40	126	2
6 – Hot air	44.0	29	133	2
Steam [16]	44.3	36	77	3

Based on the results obtained, it can be seen that heating the atomizer, in the case of compressed air, makes it possible to slightly reduce the content of CO in the combustion products, but at the same time there is a slight increase in the content of NO_x. However, the use of cold air does not allow for a significant reduction, as in the case of superheated steam, and the

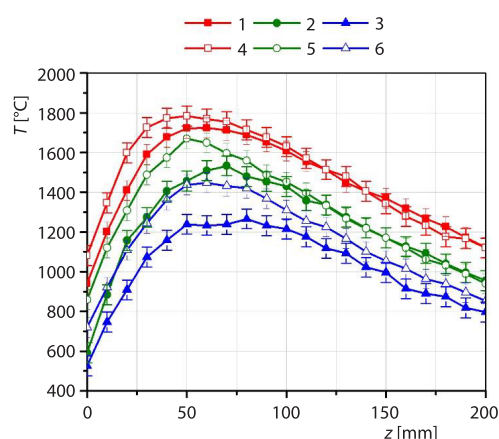


Figure 4. Average temperature distribution along the vertical axis of the burner nozzle

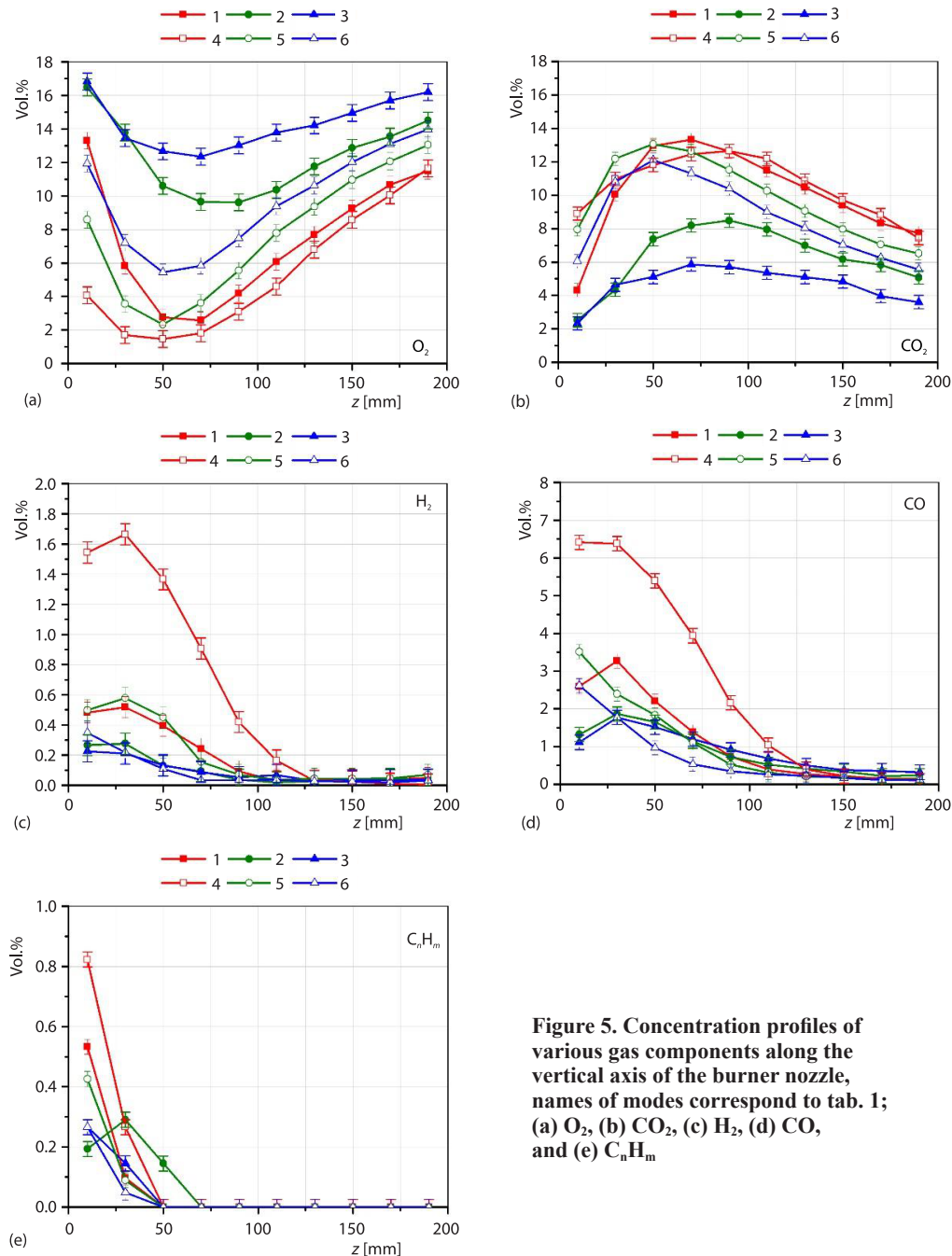


Figure 5. Concentration profiles of various gas components along the vertical axis of the burner nozzle, names of modes correspond to tab. 1; (a) O_2 , (b) CO_2 , (c) H_2 , (d) CO , and (e) C_nH_m

obtained values allow us to classify the device when spraying with air, both room temperature and heated, only to the second class according to the standard [17].

It is worth noting that in [12, 15] a similar level of decrease in the maximum temperature value in the flame was observed, similar to fig. 4 more than 100° , when atomizing fuel with

superheated water vapor. The work concluded that in the case of using steam, the maximum flame temperature is reduced due to dilution of the fuel mixture with ballast gas, which ensures a significant reduction in the content of nitrogen oxides in the exhaust gases. However, as can be seen from tab. 2, in the case of supplying air at room temperature, compared to heated air, such a decrease is not observed with similar other parameters. It can be concluded that the positive effect of superheated water vapor on the combustion of liquid hydrocarbons is associated not only with the dilution of the fuel mixture with ballast gas, but also with an additional influence on the course of chemical reactions, including as a third body.

Conclusions

The research on the ecological and thermal indicators of the combustion of liquid hydrocarbons, atomized by cold and heated compressed air, was conducted using diesel fuel as an example. A comparison was made with the method previously proposed by the authors for burning fuel in a stream of superheated steam at equivalent values of the dynamic impact of the atomizer-diluter jet on the fuel flow.

The main characteristics of the combustion process were studied, including flame temperature, composition of intermediate and final combustion products, and heat release at various operating modes of the burner device.

When analyzing the intermediate combustion components along the symmetry axis of the flame, it was noted that the use of cold air as atomizer leads to a delayed ignition of the fuel mixture, resulting in a lower flame temperature. The reduction in maximum flame temperature can reach 200 °C. Meanwhile, there is a slight decrease in NO_x emissions with an increase in CO emissions in the exhaust gases. Increasing the temperature of the air-atomizer from 20-250 °C leads to a 25% reduction in CO emissions, while the increase in NO_x is insignificant (about 5%).

Comparison of the obtained values of CO and NO_x for modes with air and steam as an atomizer showed that the use of steam leads to better ecological indicators. The NO_x emissions are reduced by 40% at a comparable level of CO emissions.

It is concluded that the positive influence of superheated water vapor on the combustion of liquid hydrocarbons is associated not only with diluting the fuel mixture with a ballast gas but also with additional effects on the progress of chemical reactions, including as a third body.

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