Measurements of the gas composition in the flame during evaporating diesel fuel combustion with steam injection

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Abstract. This paper presents a study of the effect of superheated water steam on the combustion of liquid hydrocarbons such as diesel fuel. An experimental study of the content of intermediate components of the combustion process along the axis of flame symmetry inside the burner and in the external torch was carried out using a vaporizing burner with a forced superheated water steam supply to the area of incomplete oxidation of liquid hydrocarbon fuel. The values of oxygen, carbon monoxide, hydrogen, hydrocarbons, and carbon dioxide content were also obtained. It is shown that the content of flame intermediate components of the burner depends on operating parameters such as the steam flow rate or heated air flow rate and the type of the supplied substance.

1. Introduction
The addition of water and steam has many practical applications, for example, injection of water or steam into the combustion area can significantly reduce the nitrogen oxides formation. The authors of the paper [1] point out that it is possible to significantly reduce the NOx content in the exhaust gases by steam injection into the combustion chamber. However, at a high steam flow rate, the trend towards NOx reduction stops. It is shown in [2] that direct injection of steam into the ignition region is effective to reduce NOx formation. Also, in [3] it is noted that to reduce the formation of nitrogen oxides, it is necessary to add steam to the zone of the maximum flame temperature, while in [4] it is proposed to inject steam into the zone at the end of the flame.

In addition to NOx reduction, the steam can be used to bind carbon dioxide (CO2) in oxygen combustion [5]. In this process, pure oxygen is mixed with steam and the resulting oxidant mixture is sent to the combustion boiler with fossil fuel. The advantage of this method is that flue gas recirculation is avoided. It is shown in [6] that when CO2 is completely replaced by H2O for oxygen combustion (replacing the use of recirculated gases with steam), a higher temperature is observed in the combustion chamber due to the lower volume heat capacity of the steam. In [7] it is demonstrated that in the case of oxygen combustion with a variation in the proportion of oxygen-steam, the proportion of gasification reactions increases with increasing water steam concentration, while the proportion of oxidation reactions decreases.

There is also an area of development related to the use of water and steam in the refining industry. For example, work [8] shows the influence of steam on a significant reduction in coke formation during heavy oil combustion. Also, the use of water or steam makes it possible to effectively decompose heavy residues of oil refining [9], [10].
In addition, there are burners [11] in which superheated water steam is used to remove gaseous fuel components evaporating from the surface. In work [12], using the example of a vaporizing burner device with a forced jet of superheated water steam into the zone of incomplete oxidation of liquid hydrocarbon fuels, it was shown that when diesel fuel is burned in such a device, the use of steam makes it possible to achieve high levels of fuel combustion efficiency with simultaneously low content of nitrogen oxides in the combustion products.

Despite the existing work on the influence of water and steam on the combustion process, the article [12] does not assess the intermediate conversion of fuel components with steam in any way, so it is difficult to properly assess the contribution of water and steam to the processes.

Therefore, the purpose of this work is to carry out an experimental study of the gas composition of flame intermediate components when burning diesel fuel in an evaporative burner with a forced jet of superheated water steam or, instead of the steam, heated air in the zone of incomplete oxidation of liquid hydrocarbon fuels. The results obtained are necessary for mathematical modeling of the processes under study, as well as for the creation of new environmentally friendly technologies for the disposal of liquid combustible waste with thermal energy production.

2. Experimental setup

In this work, we used a vaporizing burner with a forced superheated water steam supply to the area of incomplete oxidation of liquid hydrocarbon fuel. The start and operation of the device are described in detail in [12].

A special feature of the burner is that liquid fuel enters the burner furnace. During the burner operation, achieved temperature parameters allow the fuel in the furnace to evaporate from the free surface. At the same time, there are holes in the furnace that allow air to enter the burner device from the environment. In this way, the gaseous components of the fuel ignite under the influence of temperature in the lack of an oxidizer. The products of incomplete oxidation of liquid fuels pass through the gas generation chamber, where superheated steam is injected, which probably leads to partial gasification of the components. As a result, combustible components obtained from the incomplete oxidation of liquid hydrocarbons and from their partial steam gasification leave the burner and burn out as the oxidizer enters from the ambient air. Such scheme implementation of liquid hydrocarbons combustion in the vaporizing burner with a forced jet of superheated water steam ensures high completeness of fuel combustion with simultaneously low levels of toxic components, in particular, nitrogen oxides.

An experimental study was carried out on a fire stand (figure 1). An experimental stand for the study of the soot-steam burning regime of liquid hydrocarbons is part of the unique research facility USU “Large-scale thermo-hydrodynamic setup for studying the thermal and gas-dynamic characteristics of power plants” [13]. The experimental setup consists of a liquid fuel supply and heating system (fuel flow rate \( F_f = 0.4 \div 2.2 \text{ kg / h} \)); water supply systems (flow rate \( F_v = 0.2 \div 1.4 \text{ kg / h} \)); electric steam generator (steam overheating degree \( T_s \) up to 400 degrees); air supply systems, instead of steam (flow rate \( F_a = 0.3 \div 1.0 \text{ kg / h} \)); burner device.

A Test-1 gas analyzer was used to perform the gas analysis. The instrument was used to measure the following values: CO (0-10 % vol.), \( \text{H}_2 \) (0-40 % vol.), \( \text{C}_m\text{H}_n \) (0-20 % vol.), \( \text{CO}_2 \) (0-20 % vol.), \( \text{O}_2 \) (0-21 % vol.). The connection diagram of the gas analyzer is shown in figure 2 (a). The gas sampling for the analysis was carried out using a cooled probe (figure 2 (b)). The sample taken from the flame is cooled to room temperature directly in the probe to 'freeze' the processes in progress and to obtain reliable data on the gas composition of the intermediate components.

To carry out measurements at various points of the flame, the sampling probe was placed on an automated coordinate-moving device (moving step 1 mm). The time of sampling at one point is 80 seconds: 70 seconds the sensor values reached stationary indicators and 10 seconds on measuring. The data collection frequency is 1 Hz. After each measurement, the sensor was blown 30 s with air.
The flame temperature is measured by platinum-rhodium-platinum-rhodium thermocouple type B (Pt-30%, Rh / Pt-6%, Rh). Wire diameter is 0.3 mm. Temperature profiles were measured on the axis of symmetry of the burner.

3. Results
In the study of flame intermediate components during the combustion of diesel fuel in a vaporizing burner, experiments were carried out under various operating parameters at a constant fuel flow rate \( F_f = 0.8 \text{ kg/h} \). Steam flow rates were selected in accord with [12], the optimal operating mode of the burner at a steam consumption of \( F_v \) equal to 0.8 kg/h was chosen, and the limit values of \( F_v \) equal to 0.2 and 1.0 kg/h were chosen. The steam temperature was constant \( T_s = 260 \pm 10^\circ\text{C} \). Experimental studies were also conducted where compressed heated air from the central line was supplied instead of steam. For diesel fuel combustion modes with heated air jet supply, the \( F_f \) fuel consumption was also 0.8 kg/h, while the \( F_a \) air flow rate was equal to 0.4, 0.8, and 1.0 kg/h. The temperature of the supplied air was also set at a constant \( T_a = 260 \pm 10^\circ\text{C} \).

For the modes under study [12], the gas composition of diesel fuel combustion products in the vaporizing burner was shown (Table 1):

![Scheme of the fire stand.](image1)

![Flame sampling scheme, (b) cooling probe scheme.](image2)
Table 1. The gas composition of products of combustion during diesel fuel combustion in a vaporizing burner with a forced supply of superheated water steam [12] and heated air to the area of incomplete oxidation of liquid hydrocarbon fuels.

| Supplied substance | Steam [12] | Air |
|--------------------|------------|-----|
| $F_i$ (kg h$^{-1}$) | 0.8        |     |
| $F_s$, $F_a$ (kg h$^{-1}$) | 0.2, 0.8 | 1.0, 0.4 | 0.8, 1.0 |
| $T_s$, $T_a$ (°C) | 260±10 |     |
| [O$_2$] (vol. %) | 6.8, 10.5, 11.1 | - | 11.1, 11.4 |
| [CO] (ppm) | 0, 3, 21 | - | 1, 6 |
| [NO$_x$] (ppm) | 55, 29, 28 | - | 54, 50 |

Figure 3 shows the results of the gas composition of intermediate components in a flame during the diesel fuel combustion in a vaporizing burner. The signatures shown in figure 3 correspond to the modes shown in Table 2.

It is shown in figure 3 that in the modes with low steam flow rate or heated air flow rate (S2D8, A4D8), the highest levels of intermediate components (CO, H$_2$, C$_m$H$_n$) are observed. This is probably because these modes provide less dilution of the components by the air entrained by the jet from the environment into both the device furnace and the external flame, resulting in an increase in the size of the external flame, as noted in [12]. This assumption is supported by minimum O$_2$ values for these modes, which only begin to grow at some considerable distance from the base of the flame (~150 mm), together with a decrease in the fraction of CO, H$_2$, C$_m$H$_n$ and an increase in CO$_2$, which indicates a long time for the oxidation reaction of the fuel.

Table 2. Symbols of regimes for diesel fuel combustion.

| Steam   | Air   |
|---------|-------|
| $F_i$ (kg h$^{-1}$) | $F_i$ (kg h$^{-1}$) | $P$ (bar) | $F_i$ (kg h$^{-1}$) | $F_i$ (kg h$^{-1}$) | $P$ (bar) |
| S2D8    | 0.2   | 0.6   | A4D8    | 0.4   | 1.5   |
| S8D8    | 0.8   | 0.8   | 4.3     | A8D8   | 0.8   | 3     |
| S10D8   | 1.0   | 5.3   | A10D8   | 1.0   | 4.7   |
Figure 3. The gas composition of flame intermediate components during diesel fuel combustion in the vaporizing burner with the forced jet of superheated steam or heated air into an area of incomplete oxidation of liquid hydrocarbon fuels.

The maximum values of CO and H₂ content for all modes and types of supplied jets are located at the base of the flame, while for each type of supplied jet, their maximum values for all investigated steam or air flow rates coincide within the error limits. At the same time, for different types of jet, the volumetric contents of CO and H₂ are also different (the values are higher when using a heated air jet) along the axis of symmetry of the flame, while they also take minimum values at the same distance from the base of the flame.

The maximum values of CₘHₙ content are also observed at the base of the flame. In modes with low steam flow rate or air flow rate (S2D8, A4D8) a sharp increase in CₘHₙ is observed, which may be associated with increased soot formation for these modes, due to the small amount of air entrained in by the jet from the environment in comparison with other modes.

When considering the content of O₂ and CO₂ in the flame of the burner device, it can be noted that at a distance of 200 mm from the base of the flame, the values of the content of the components are close to the values obtained on the calorimeter (Table 1) [12], with the correction for the fact that the current data were obtained on an open stand, as a result, there are small differences in the values of O₂ and CO₂. Thus, the obtained values of the various intermediate components along the axis of
symmetry of the flame can be used to evaluate and describe the processes taking place in the flame in general.

4. Conclusion
This work is devoted to an experimental study of the gas composition of intermediate components in a flame during diesel fuel combustion in a vaporizing burner with a forced jet of superheated water steam or heated air in the area of incomplete oxidation of liquid hydrocarbon fuels.

It is found that the maximum values of the volumetric concentrations of intermediate components (CO, H₂, and CₘHₙ) are reached at the base of the flame when the combustible gases leave the burner. In this case, the maximum values of CO and H₂ coincide within the error limits for different modes, and a sharp increase in the value of CₘHₙ is also observed in modes with low parameters of the steam or air jet supply (S2D8, A4D8). For different types of jet, the volumetric contents of CO and H₂ are different along the axis of symmetry of the flame; when using a heated air jet, the values are higher, while they take the minimum values at the same distance from the base of the flame.

The experimental data obtained can be used to mathematical model and to clarify the processes occurring when superheated water steam is used in the combustion of liquid hydrocarbon fuels.

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