

Influence of Preparation and Combustion Parameters of Coal-water Slurries on Gas Emission Chemistry

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Abstract

The article presents the results of experimental studies performed for the comparative analysis of factors affecting the concentration of the main gas emissions during the combustion of fuel suspensions obtained from coal enrichment waste. The factors influencing the formation of anthropogenic emissions during the flaring of coal-water fuel suspensions were investigated. Experiments were carried out with coal processing waste, both with and without additives in the form of spent mineral oil. The article shows how the concentration of sulfur dioxide, nitrogen dioxide, and hydrocarbons is affected by the parameters of preparation (particle size, solid-liquid phase ratio, additives of used engine oil) and combustion (temperature in the combustion chamber, excess air coefficient, and droplet size after spraying) of fuel suspensions.

Introduction

The demand for high-calorie coals is growing every year. This leads to an increase in the productivity of existing processing plants, the commissioning of new coal processing facilities and, as a result, an increase in the volume of waste generation. Currently, the amount of accumulated waste from coal processing in Russia is comparable to the reserves of developed deposits, and the annual increase reaches tens of percent of the total production volume. According to their fuel characteristics, such waste is often not inferior to the extracted solid mineral fuel. Today, waste from coal enrichment is usually placed in dumps, which leads to the withdrawal of agricultural, forestry, and other lands for their placement. The fire-hazardous technogenic objects formed in this way, containing fine coal particles, are sources of pollution of the surface layer of atmospheric air, soils, surface and underground waters, as well as the cause of deterioration of public health and increased mortality in certain regions. An effective solution for the disposal of accumulated and annually generated waste of coal enrichment will reduce the industrial burden on the environment in the zone of impact of coal processing enterprises, lower the loss of energy raw materials and reduce the costs of enterprises for the production of thermal energy (Bazhin 2016, Borowski and Ozga 2020).

Currently, there are a large number of possible ways to dispose of carbon-containing waste-this is briquetting, gasification, dust-coal combustion, etc. However, these methods do not allow to immediately process the resulting waste and require preliminary removal of moisture (Alexandrova and Rasskazovav 2016, Borowski at al. 2020). One of the most promising ways to dispose of waste from coal processing today is their use as raw materials for the production of fuel suspensions. This method allows the processing of watered waste immediately after its formation, which eliminates its interaction with the components of the natural environment. This reduces the negative impact on all environmental compartments, as well as simplifies and reduces the cost of fuel preparation due to the lack of costs for primary preparation associated with grinding and drying waste (Silyutin and Epshtein 2020).

The ability to control the process of thermal waste disposal allows to significantly reduce the emissions of pollutants into the air. In this regard, of particular interest is the theory of CWS burning process, as well

as the ability to control the combustion process by adjusting the parameters of their preparation and combustion and the possibility of reducing the concentration of pollutants in the exhaust gas. The aim of this work is to experimentally study the factors affecting the concentration of the most dangerous components of gaseous emissions during the combustion of fuel suspensions obtained from coal enrichment waste in order to establish the best energy and environmental indicators for the thermal disposal of coal enrichment waste.

Experimental Setups, Methods, And Materials

To be able to control the combustion process and obtain the best fuel and environmental characteristics in the thermal disposal of coal enrichment waste, it is necessary to consider the influence of the main parameters of preparation, spraying, and combustion of fuel suspensions.

The following parameters of the preparation of fuel suspensions affect the emissions of pollutants: grinding coarseness, the ratio of the dispersed and dispersion phases of the suspension, and fuel composition. During combustion of the suspension fuel, the composition of waste gases is affected by the following parameters: temperature in the active combustion zone, air-fuel ratio, and droplet size for spray equipment (Shabarov and Nikolaeva 2016).

As a raw material for the preparation of fuel suspensions, slurries from the gravitational enrichment of various coal rank from the Kemerovo region (Russia) were used. The main characteristics of coal processing waste are presented in Table 1.

Table 1
Main characteristics of coal processing waste

Parameter	A ^d (%)	Q _i ^d (MJ/kg)	V ^{daf} (%)	C ^d (%)	H ^d (%)	N ^d (%)	S ^d (%)	O ^d (%)
Value	29.9	17.5	45.8	56.8	3.50	1.56	0.34	7.90

For the preparation of CWS, the waste of coal enrichment was crushed and mixed with tap water. Homogenization was carried out using overhead stirrers at a rotation speed of 500 rpm for 10 minutes.

Preparation of CWSP (with the addition of used engine oil) was carried out in two stages. At the first stage, a water-oil emulsion was prepared: for this purpose, waste oil and water were mixed in a laboratory beaker for 5 minutes. After that, the crushed waste of coal enrichment was added to the tank. The duration of homogenization of the suspension was 10 minutes (Glushkov at al. 2016).

To conduct experiments on the combustion of fuel suspensions that are close to real conditions, a laboratory stand was designed, which allows conducting tests on the flaring of various types of fuels, and a two-phase pneumatic nozzle with external mixing for spraying fuel water-coal suspensions (Fig. 1).

To determine the component composition of the combustion products, depending on the different characteristics of the preparation and combustion of coal-water fuel obtained from the waste of coal

enrichment, the combustion chamber of the stand was heated to a temperature of $850 \pm 20^\circ\text{C}$. After reaching the temperature required for igniting the fuel suspensions, the blast air was switched to the mode of operation with liquid fuel sprayed by means of a nozzle (Fig. 1).

Figure 2 shows the main stages of combustion of coal-water fuel suspensions along the spray axis of flare. The lower part of Fig. 2, depicts the main possible options for the combustion of fuel droplets, depending on the spray parameters, particle size, and characteristics of the combustion of suspensions.

Spraying of coal-water fuel is carried out by air in two stages. At the first stage, the suspension jet is crushed due to the kinetic energy of the spraying agent. At the second stage, at a high speed of movement of the sprayed fuel particles, their crushing is carried out due to the resistance forces of the gas-air medium in the boiler furnace. As a result of the resulting dynamic action, the droplets are torn into smaller ones, and the liquid phase with thin carbon particles breaks off from the surface of large coal particles. When a drop of fuel interacts with a heated oxidizer, its temperature increases. This heat is spent on the evaporation of water from the surface layer, as well as on the transition of the organic component of coal to the gaseous state. When the concentration of volatile organic compounds in the vicinity of the drop reaches critical values, their ignition occurs. The heat released during combustion warms up the coke residue, the temperature rises and carbon is ignited. The length of the flame torch in the combustion of water-coal suspensions in comparison with pulverized coal combustion is 20–40% longer due to the addition of water. This contributes to a more uniform course of the combustion process, reduction of the rate of mechanical underburning, as well as reducing the concentration of hydrocarbons in the composition of the exhaust gases.

Determination of the content of pollutants in the exhaust gases from the combustion of CWS and CWSP was carried out after stabilization of the combustion parameters. The content of nitrogen dioxide, sulfur dioxide, and the content of hydrocarbons in the exhaust gases was determined using a portable multicomponent gas analyzer "POLAR" with a forced sampling device. The relative measurement error in the determination of nitrogen oxides and sulfur dioxide was less than 5%. In hydrocarbons determination, the relative error was less than 10%.

Sampling of waste gases to determine the content of hydrocarbons was carried out taking into account the recommendations presented in the article (Anichkov et al. 1985). Samples were taken by external filtration on sorption tubes filled with a universal Tenax GR sorbent under isokinetic conditions. Sampling was carried out for 2 minutes with a flow rate of pumping the gas mixture of $0.5 \text{ dm}^3 / \text{min}$. The ambient temperature during the experiments was less than 10°C ; therefore, a rapid decrease in the gas temperature along the intake pipe path was observed. An absorption solution (n-hexane) was placed behind the sorption tube to control the overshoot of hydrocarbons, which was less than 2 %. The samples were analyzed for hydrocarbon content using a GCMS-QP2010 Ultra Shimadzu gas chromatography-mass spectrometer with a Unity-2 thermal desorber.

The concentration of hydrocarbons was determined only in those experiments where, according to the literature, a change in the parameter significantly affects the content of organic compounds in the composition of waste gases during fuel combustion. These include the effect of organic compound additives, change of the temperature in the combustion chamber, and the effect of the air-fuel ratio. The obtained values of the concentrations of pollutants after measurements were recalculated for the specific gravity of their formation, referred to as 1 g of burned fuel in terms of dry state (Cheremisina and El-Salim, 2017).

The experiments were conducted at the following parameters: the average temperature in the furnace $900 \pm 20^\circ\text{C}$; excess air 30 %; average particle diameter waste coal $50 \pm 10 \mu\text{m}$; the mass ratio of waste coal/water equal to 40/60; average droplet size of the slurry during the spraying of $130 \pm 20 \mu\text{m}$. When identifying the dependences of the energy and environmental characteristics of thermal utilization, the values of only one of the studied characteristics were changed separately, while the rest were unchanged.

Results And Discussion

The results of studies of the effect of each of the parameters of fuel preparation and combustion on the concentration of pollutants separately are presented below.

3.1. Particle size distribution

Experiments to determine the effect of the fineness of grinding on the composition of waste gases were carried out for water-coal suspensions obtained from coal enrichment waste with an average particle diameter of 35, 47, 92, 154, and 202 μm . The results of studies of the content of nitrogen and sulfur oxides in the exhaust gases are shown in Fig. 3.

When drops of CWS enter the heated chamber, the temperature of the drops increases rapidly, water vapor and volatile components are released, which leads to the effect of micro-explosion (Atal and Levendis 1994). As a result, the diameter of individual droplets decreases, and the specific surface area of the sprayed fuel increases (Fig. 2). When using large particles as raw materials (the average diameter of which is 154 and 202 μm), the effect of microexplosion becomes less noticeable, which means that for the complete combustion of such fuel, a greater amount of time is required to stay in the chamber. With constant combustion parameters, an increase in the fineness of the grinding led to an increase in the combustible losses: from 1.5 % for fuel with an average particle diameter of 35 μm ; up to 11.2 % for fuels where particles with an average diameter of 202 μm were used.

An increase in the combustible losses is associated with a decrease in the concentration of pollutants in the exhaust gases with an increase in the average particle diameter. With the selected combustion parameters, suspensions with an average particle size of more than 92 μm are not completely burned out, and sulfur and nitrogen compounds remain in the organic and mineral mass of the raw material. More complete combustion of suspensions increases the energy efficiency of the fuel, reduces the danger of

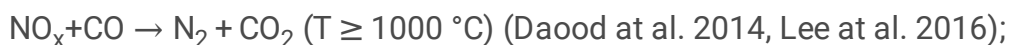
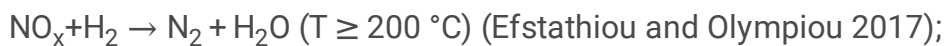
the resulting ash and slag waste to the environment. Also, the ash with a low content of organic mass can be used as an additive to asphalt and concrete without preliminary preparation.

3.2. Ratios of solid and liquid phases in the suspension composition

Experiments to determine the effect of the proportion of solid and liquid phases on the composition of waste gases were carried out for CWS with a mass ratio of waste coal/water equal to 50/50, 60/40, and 70/30. The results of studies of the content of nitrogen and sulfur oxides in the exhaust gases are shown in Fig. 4.

An increase in the proportion of solid components in the composition of fuel suspensions from coal processing waste from 50 to 70 % leads to an increase in the specific mass of the formation of sulfur oxides by 56 %, and nitrogen oxides by 27 %.

The presence of a large amount of water in the composition of fuel suspensions lowers the temperature in the zone of active combustion, which leads to a decrease in the amount of formed nitrogen and sulfur oxides. In addition, water vapor under the influence of high temperatures decomposes into oxygen and hydrogen. In this case, the oxygen formed during the reaction intensifies the combustion process, and hydrogen helps to reduce the levels of nitrogen oxides and sulfur in the exhaust gases:



Nevertheless, a decrease in the amount of the combustible component in the composition of fuel suspensions leads to a decrease in its specific heat of combustion, reduces the stability of the flame combustion, and also increases the ignition time of the suspension droplets, which negatively affects the energy characteristics of combustion. It was found that the best combustion parameters are observed with a solid content of 55–60 wt. %.

3.3. Waste mineral oil additives

Studies to determine the effect of the addition of spent mineral engine oil to fuel suspensions on the composition of waste gases were carried out at the mass ratio of coal enrichment waste/waste oil/water: 60/0/40, 55/5/40, 50/10/40, and 45/15/40.

Used engine oil has a high specific heat of combustion, 45.8 MJ/kg. When it is used as an additive to fuel suspensions, the total specific heat of combustion increases, the droplet ignition time decreases, and the flame stability increases. When 5% of used engine oil is added to the suspension from coal enrichment

wastes, the specific heat of combustion increases by 13%, with the addition of 10% by 25%, at 15% by 37%.

Table 2 shows the concentrations of the main groups of hydrocarbons formed during the combustion of CWSP using used engine oil as an additive.

Table 2

Concentration of basic hydrocarbons depending on the content of used engine oil in the suspension

Group of hydrocarbons	The concentration of hydrocarbons, depending on the mass ratio of coal waste/waste oil/water (mg/g)			
	60 / 0 / 40	55 / 5 / 40	50 / 10 / 40	45 / 15 / 40
Saturated hydrocarbons	0.42	0.25	0.21	0.19
Unsaturated hydrocarbons	0.62	0.79	0.87	0.94
Oxygen organic compounds	3.88	4.24	4.64	4.97
Polyaromatic hydrocarbons:	< 0.001	0.001	0.002	0.005
Naphthalene	< 0.001	< 0.001	0.001	0.001
Anthracene	0.002	0.003	0.005	0.008
Phenanthrene	0.003	0.004	0.004	0.005
Pyrene	< 0.001	< 0.001	0.002	0.005
Benzo[a]pyrene	< 0.005	0.01	0.03	0.05
Xylene				
Amount of hydrocarbons	4.98	5.35	5.81	6.22

The addition of waste oil to coal-water suspensions leads to an increase in the total amount of hydrocarbons in the exhaust gases. The content of unsaturated, oxygen-containing and polyaromatic hydrocarbons increases, while the content of limiting hydrocarbons decreases. Also, when adding oil in the composition of the exhaust gases, xylenes can be fixed, which were not detected when burning coal-water fuel without additives (Table 2).

The increase in the content of unsaturated hydrocarbons in the composition of the exhaust gases is presumably associated with an increase in temperature in the zone of active combustion of the flame, which leads to incomplete pyrolysis of saturated hydrocarbons, in addition, the presence of additives in the waste oil containing metals such as Zn, Mo, Cu, etc., can catalyze the reactions of intermolecular

dehydrogenation of saturated hydrocarbons upon rapid cooling of a highly heated gas-air mixture (Yan et al. 2020).

The increase in the concentration of oxygenated hydrocarbons is due to the presence of esters in the waste oil. The content of PAHs in the exhaust gases increases due to an increase in the amount of volatiles in the CWSP.

To visualize the obtained data, a graph of the dependence of the specific mass of nitrogen oxides, sulfur oxides, and the amount concentration of hydrocarbons on the addition of used engine oil to fuel coal-water suspensions obtained from coal processing waste was plotted (Fig. 5).

The sulfur content of the waste oil is 0.49 %. This indicator is slightly higher than for coal enrichment waste (0.32 %). The nitrogen content in the waste oil is 0.13 %, which is lower than in coal processing waste, where this value is 1.50 %.

An increase in the content of used engine oil in the composition of fuel suspensions during combustion leads to an increase in the concentration of nitrogen oxides in the composition of exhaust gases due to an increase in temperature in the active combustion zone. Also, the content of sulfur dioxide increases slightly due to an increase in the sulfur content in the combustible mass of the fuel (Poskart and Lech 2007).

When even 5% of used engine oil is added to the suspensions, their ignition is greatly simplified due to the relatively low ignition temperature of the oil, which is 226 ° C. For coal-water suspensions, the ignition temperature is 800–850 ° C. Also, when using the additive in the form of waste oil, the sedimentation stability of the suspension significantly increased (Samoilik et al. 1990, Debadutta 2020).

Since the parameters of the coal enrichment waste generated at the enterprise can differ significantly even during one shift, for the stability of combustion and obtaining the required energy parameters, it is possible to control the characteristics of the fuel by adding used oils.

3.4. Combustion temperature

Experiments to determine the effect of the combustion temperature on the composition of waste gases were carried out for fuel CWS at temperatures of 800 ± 20 °C, 900 ± 20 °C, 1000 ± 20 °C и 1100 ± 20 °C. Table 3 shows the concentrations of the main groups of hydrocarbons formed during the combustion of fuel suspensions, depending on the temperature in the combustion chamber.

Table 3

Concentration of basic hydrocarbons depending on the temperature in the combustion chamber

Group of hydrocarbons	The concentration of hydrocarbons, depending on the temperature in the combustion chamber (mg/g)			
	800 °C	900 °C	1000 °C	1100 °C
Saturated hydrocarbons	0.73	0.42	0.34	0.29
Unsaturated hydrocarbons	1.15	0.62	0.41	0.35
Oxygen organic compounds	4.73	3.88	2.94	2.32
Polyaromatic hydrocarbons:	0.002	< 0.001	< 0.001	< 0.001
Naphthalene	0.001	< 0.001	< 0.001	< 0.001
Anthracene	0.002	0.002	0.002	< 0.001
Pyrene	0.003	0.003	0.002	< 0.002
Benz[a]anthracene	0.002	< 0.001	< 0.001	< 0.001
Benzo[a]pyrene				
Amount of hydrocarbons	6.63	4.93	3.71	2.99

The specific mass of the formation of hydrocarbons at higher temperatures decreased. The ratio of saturated, unsaturated, oxygen-containing, and polyaromatic organic compounds remained practically unchanged with increasing temperature.

The graph of the change in the mass of formation of nitrogen oxides, sulfur dioxide and hydrocarbons with a change in the combustion temperature of CWS obtained from coal wastes is shown in Fig. 6.

As the temperature rises, the concentration of sulfur dioxide increases. At high temperatures, the rate of the oxidation reaction increases, and the process of interaction of fuel sulfur with oxygen intensifies (Matveeva et al. 2019).

Nitrogen oxides during fuel combustion are formed from nitrogen-containing fuel components and molecular nitrogen in the air. During the experiments, it was found that the high-temperature effect in the combustion zone has a decisive influence on the content of nitrogen oxides in the exhaust gases. The formation of thermal nitrogen oxides occurs by the Zeldovich mechanism (Zeldovich et al. 1947, Babiy et al. 1996), in which the blast nitrogen is oxidized in the zone of active flame combustion. Since the

activation energy of these reactions is high, the content of nitrogen oxides in the exhaust gases strongly depends on the temperature.

3.5. Air–fuel ratio

Experiments to determine the effect of air–fuel ratio during combustion of fuel suspensions obtained from coal processing waste on the composition of waste gases were carried out at air–fuel ratio of 1.1, 1.2, 1.3, and 1.4 %. Table 4 shows the values of the concentrations of the main groups of hydrocarbons formed during fuel combustion, depending on the air–fuel ratio.

Table 4
The concentration of the main hydrocarbons, depending on the air-fuel ratio

Group of hydrocarbons	The concentration of hydrocarbons, depending on air-fuel ratio (mg/g)			
	1.1	1.2	1.3	1.4
Saturated hydrocarbons	1.12	0.64	0.42	0.32
Unsaturated hydrocarbons	2.32	1.14	0.62	0.46
Oxygen organic compounds	4.62	4.21	3.88	3.32
Polyaromatic	0.011	0.003	< 0.001	< 0.001
hydrocarbons:	0.029	0.009	< 0.001	< 0.001
Naphthalene	0.023	0.007	0.002	< 0.001
Anthracene	0.005	0.004	0.003	< 0.002
Pyrene	0.006	0.003	< 0.001	< 0.001
Benz[a]anthracene				
Benzo[a]pyrene				
Amount of hydrocarbons	8.20	6.14	4.93	4.17

An increase in the excess air, calculated from the stoichiometric equation of combustion of a fuel suspension, from 1.1 to 1.4 leads to a decrease in the specific gravity of the formation of hydrocarbons by almost 2 times. This also reduces the levels of carcinogenic PAHs such as anthracene, pyrene, benzo[a]pyrene, benz[a]anthracene, and naphthalene.

For visualization of the obtained data was constructed a graph of the specific gravity of the formation of nitrogen oxides, sulfur dioxide, and total hydrocarbons from the excess air ratio when burning fuel suspensions obtained from by-product coal (Fig. 7).

Figure 7 shows a significant decrease in the specific mass of the formation of hydrocarbons, but at the same time, the amount of nitrogen oxides increases. The specific gravity of the formation of sulfur dioxide is less dependent on the air-fuel ratio.

With a decrease in the air-fuel ratio, the volumes of the formed thermal nitrogen oxides also decrease. At the same time, an insufficient excess of air in the combustion zone leads to an increase in emissions of hydrocarbons and particulate matter. Also, the regulation of the formation of nitrogen oxides by changing the excess air ratio can lead to high-temperature sulfide corrosion and increase the slagging of the walls of the furnace of the boiler unit. Despite this, the combustion of fuels with a lack of air is one of the most common ways to control nitrogen oxide emissions (Li et al. 2013, Hu et al. 2000).

The lowest amount of pollutants in the exhaust gases during the combustion of fuel suspensions from coal enrichment waste is observed at an air-fuel ratio of 1.2–1.3.

3.6. Suspension droplet size

Experiments to determine the effect of the degree of suspension spraying on the composition of waste gases were carried out for water-coal suspensions obtained from coal enrichment waste with an average drop diameter of 65, 94, 128, 184, and 253 μm . The results of studies of the content of nitrogen oxides and sulfur in the exhaust gases are shown in Fig. 8.

An increase in the average droplet size when spraying the suspension leads to a decrease in the specific mass of nitrogen and sulfur oxides. This is due to the fact that with an increase in the diameter of the drop, more time is required for its heating and ignition. Larger drops during the combustion of suspensions do not have time to completely burn out, as a result of which the combustible losses increases. This is associated with a decrease in emissions of nitrogen oxides and sulfur with an increase in the diameter of the suspension droplets.

The droplets with an average diameter of 65 microns burned more intensively, as a result of which the temperature in the combustion chamber increased and because of this, there was an increase in the concentration of nitrogen oxides and sulfur oxide in the composition of the exhaust gases. The microexplosion effect less apparent for drops of this diameter (Gaber et al. 2020).

The most optimal solution is to spray CWS to droplets with an average size of 94–128 μm since this requires less energy consumption compared to a suspension dispersed to droplets with an average diameter of 65 μm . The combustible losses when spraying drops with an average diameter of 65, 94, and 128 μm were 2.5–4.9 %.

Conclusions

The conducted experiments made it possible to establish the dependence of the formation of sulfur oxides, nitrogen oxides, saturated and unsaturated hydrocarbons, oxygen-containing organic compounds, as well as the main polyaromatic hydrocarbons formed during coal combustion, depending on the preparation parameters and combustion characteristics of coal-water suspensions obtained from coal enrichment waste.

The results obtained make it possible to select the best environmental and energy parameters for the combustion of fuel suspensions from coal enrichment wastes, which include: the degree of grinding is from 30 to 100 μm , the solid part content in the suspension is from 55 to 60%; adding 5% waste oil to the suspensions to obtain the best energy characteristics without a significant increase in the concentration of pollutants in the composition of the exhaust gases; the combustion temperature is in the range from 950 to 1050 ° C, the droplet size when spraying the suspension is from 50 to 150 μm .

Declarations

Ethics approval and consent to participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Ivan Sverchkov, Mariia Chukaeva and Vera Matveeva. The first draft of the manuscript was written by Ivan Sverchkov and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

- Conceptualization: IS formulated the idea of the research, VM formulated the goals and aims;
- Methodology: IS designed an experimental stand for flaring liquid fuels and set up an experiment, MC designed a method for sampling and analyzing samples;
- Formal analysis and investigation: IS, MC used statistical and mathematical methods to analyze the data obtained;
- Writing - original draft preparation: IS wrote the initial draft;
- Writing - review and editing: IS, MC prepared, created and presented the published work, VM prepared a critical review of scientific work;
- Supervision: VM carried out supervision and responsibility for the planning and execution of research activities.

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Competing Interests

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

All data generated or analysed during this study are included in this scientific work (<https://spmi.ru/sverchkov-ivan-pavlovich>).

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Figures

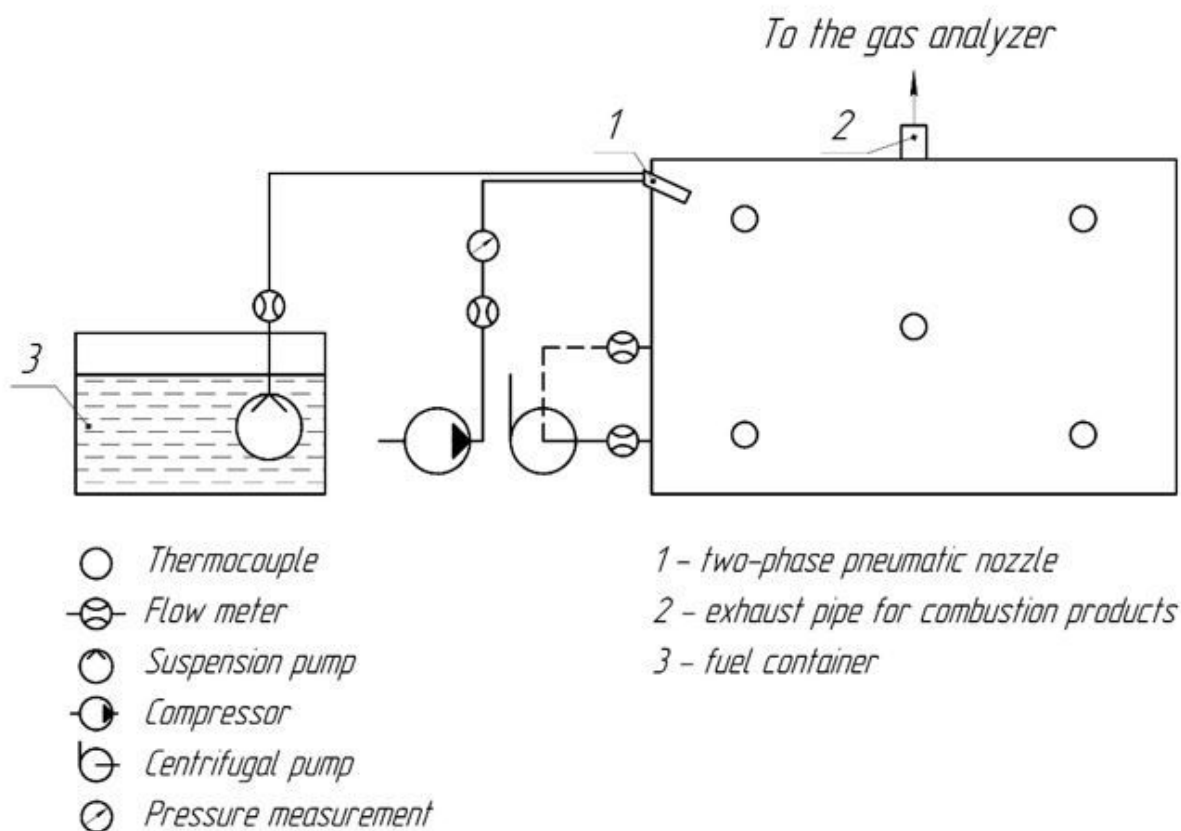


Figure 1

Scheme of an experimental stand for flaring liquid fuels

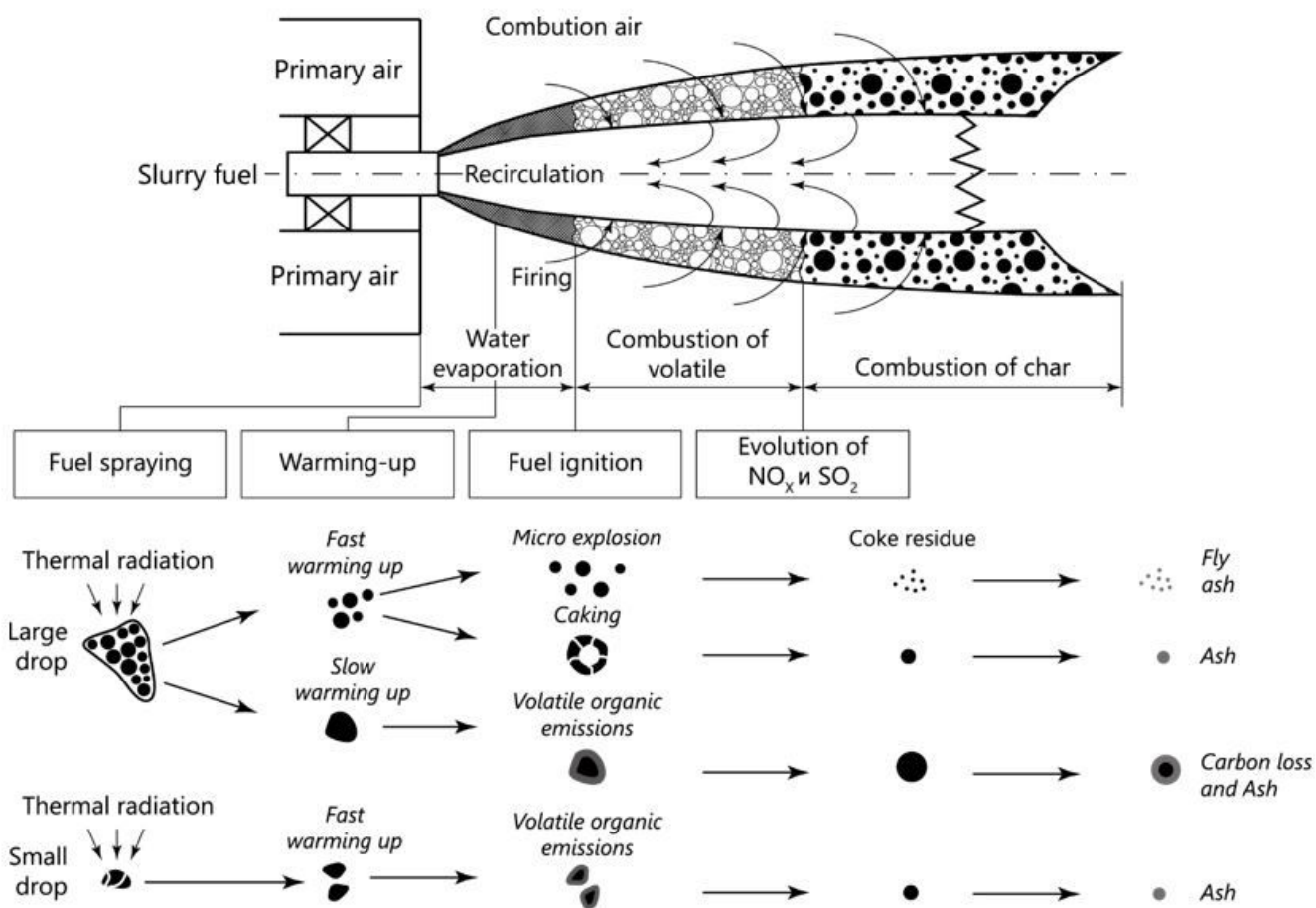


Figure 2

Combustion of CWS during flaring

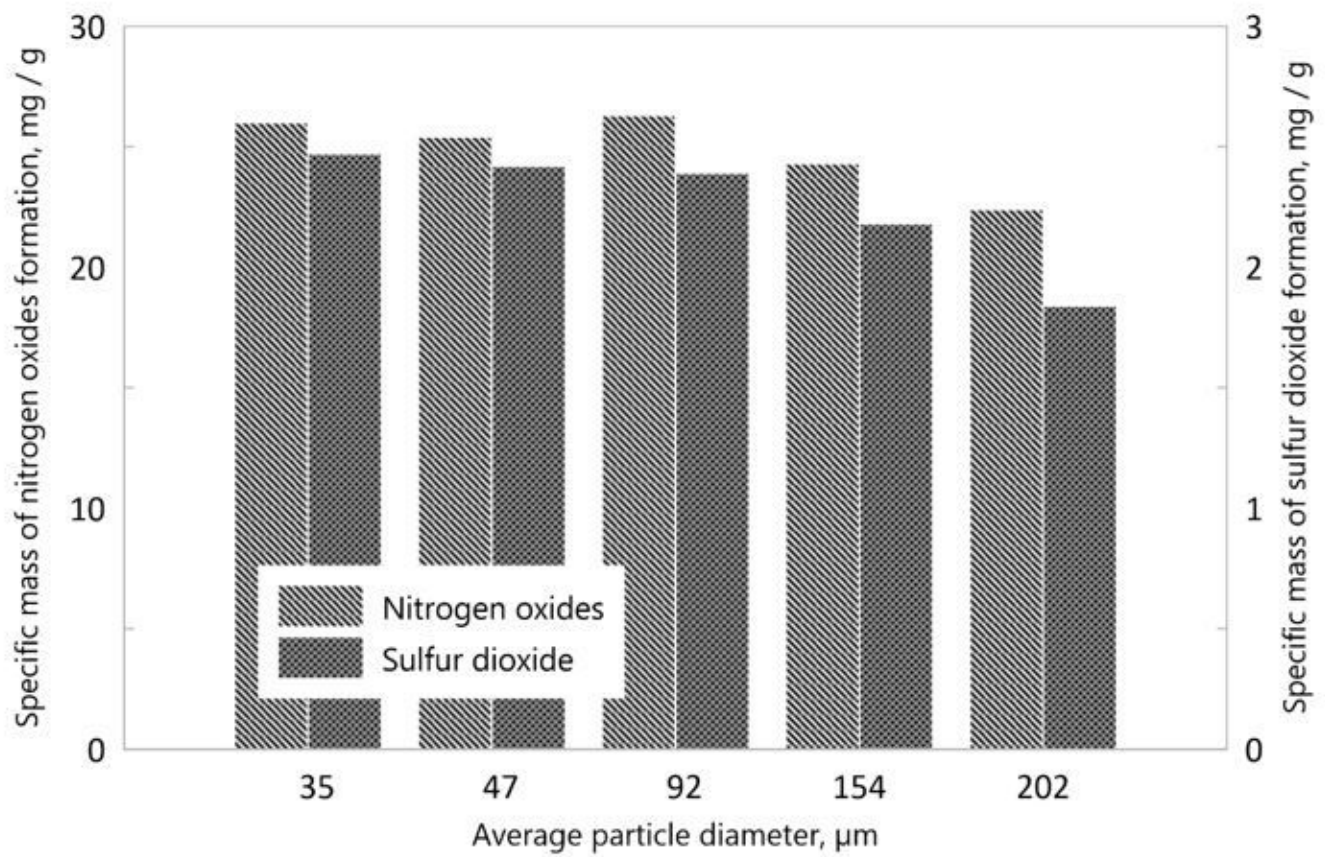


Figure 3

The effect of the fineness of by-product coal grinding on the waste gases composition

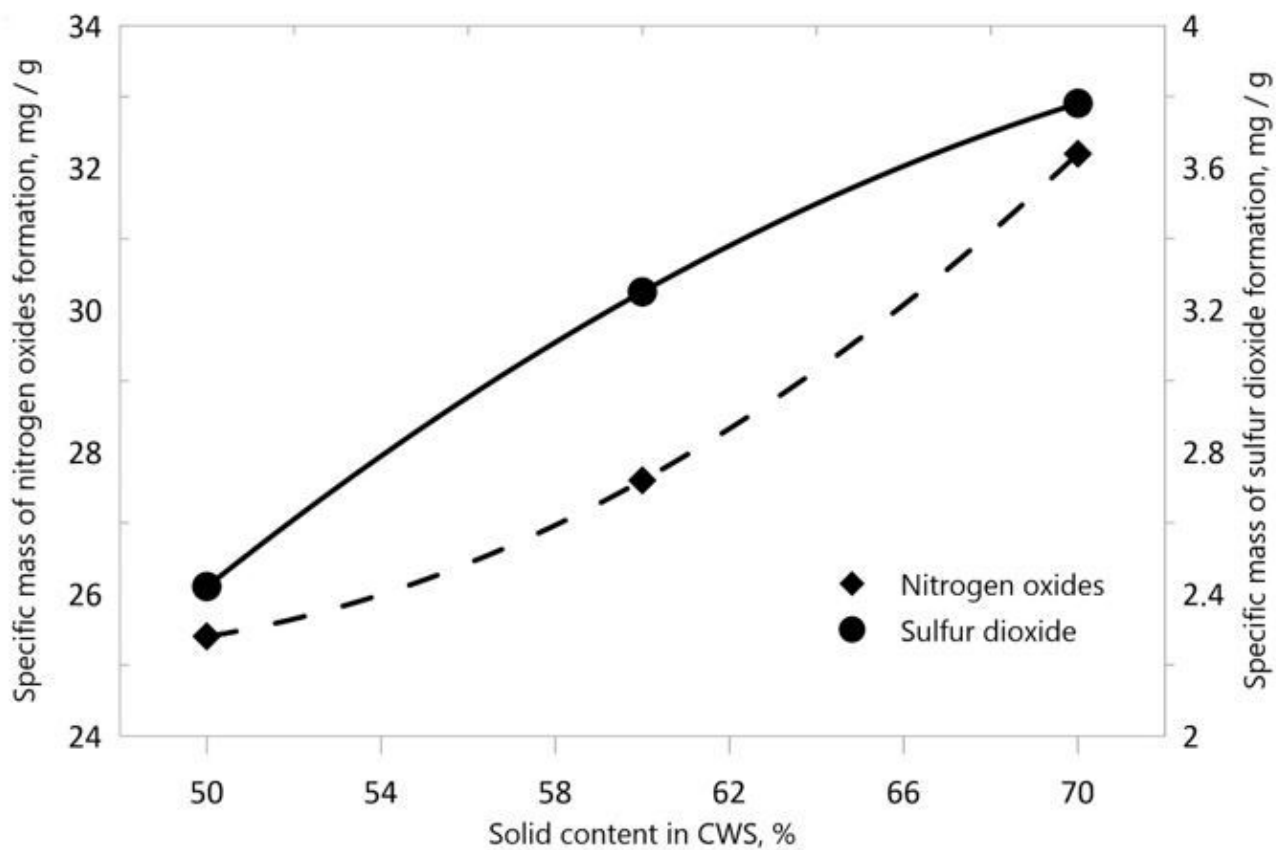


Figure 4

Effect of the solid-liquid phase ratio in the fuel on the composition of the exhaust gases

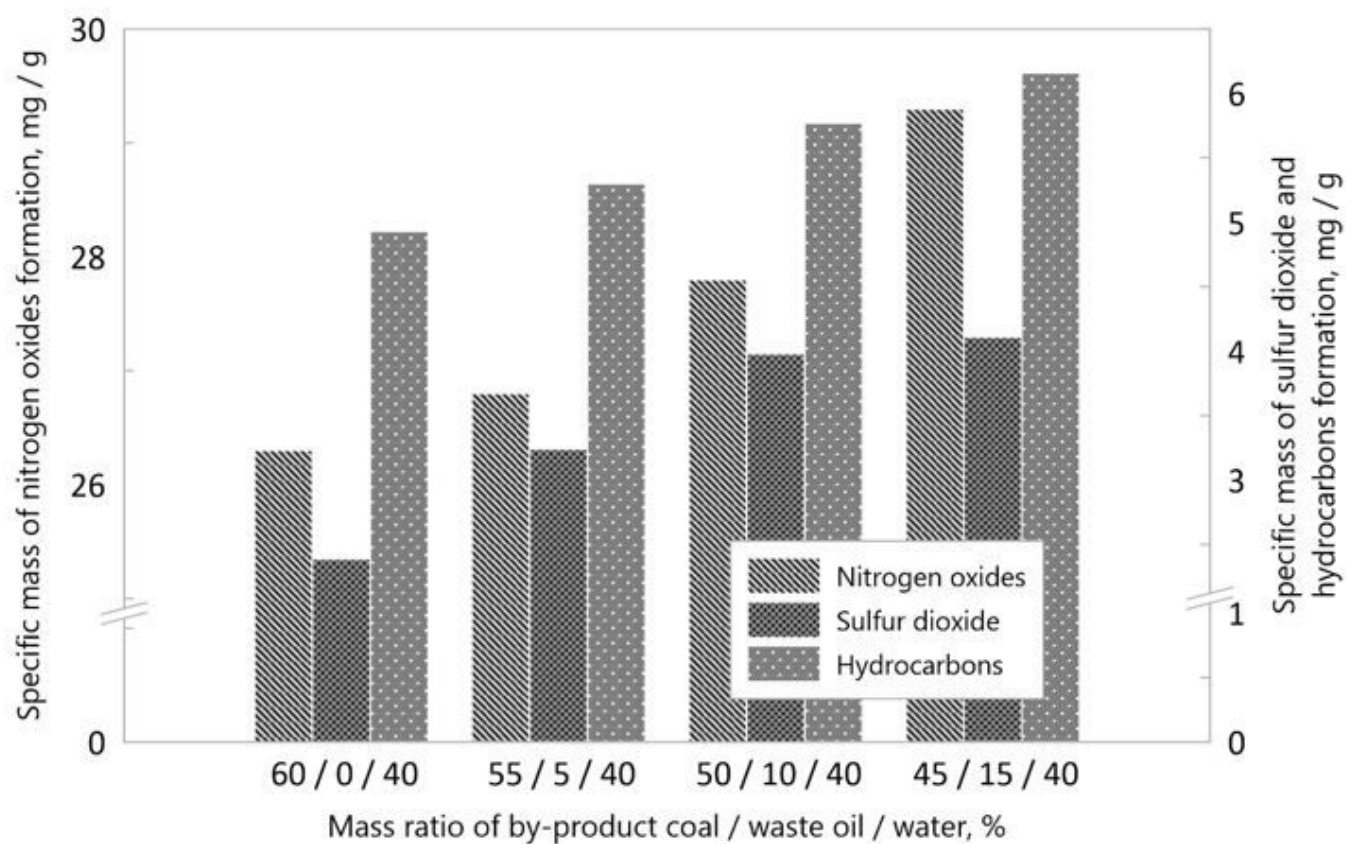


Figure 5

Influence of the content of used engine oil on the composition of exhaust gases

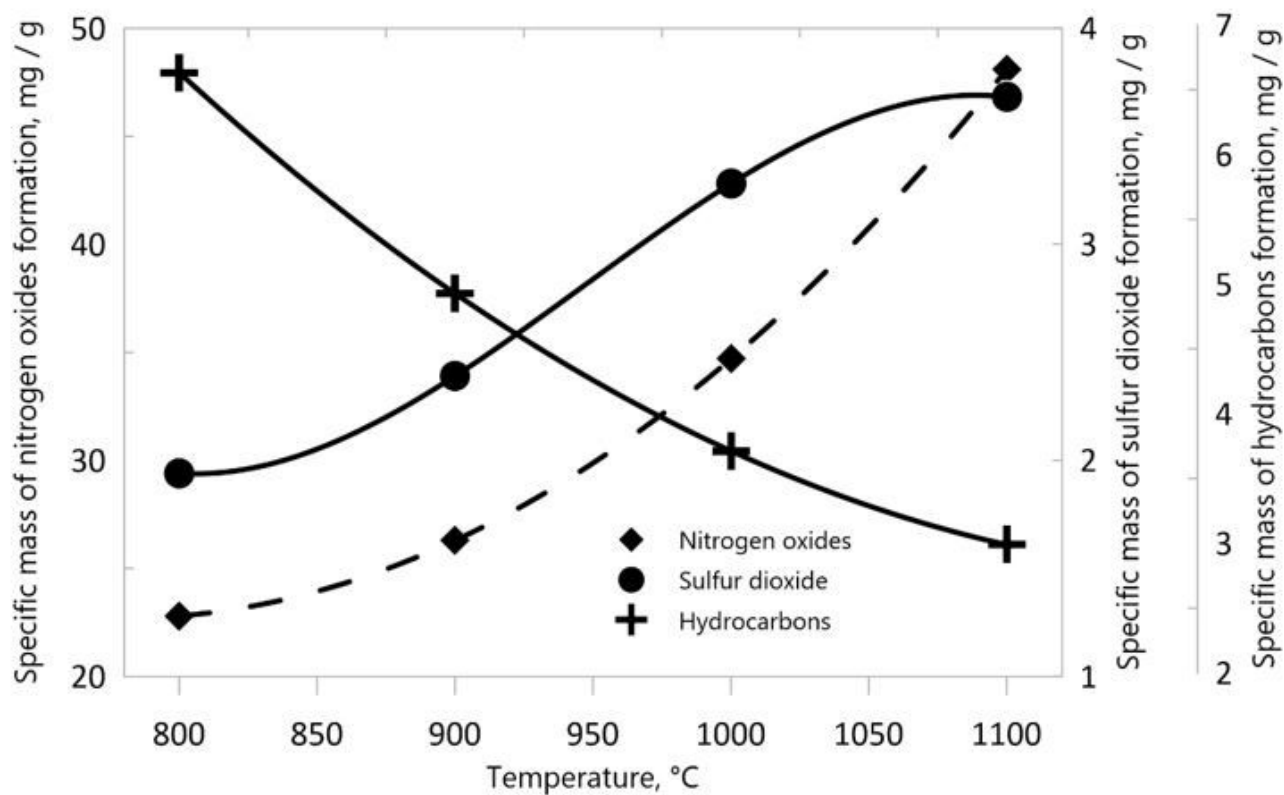


Figure 6

Influence of the temperature in the combustion chamber on the composition of the exhaust gases

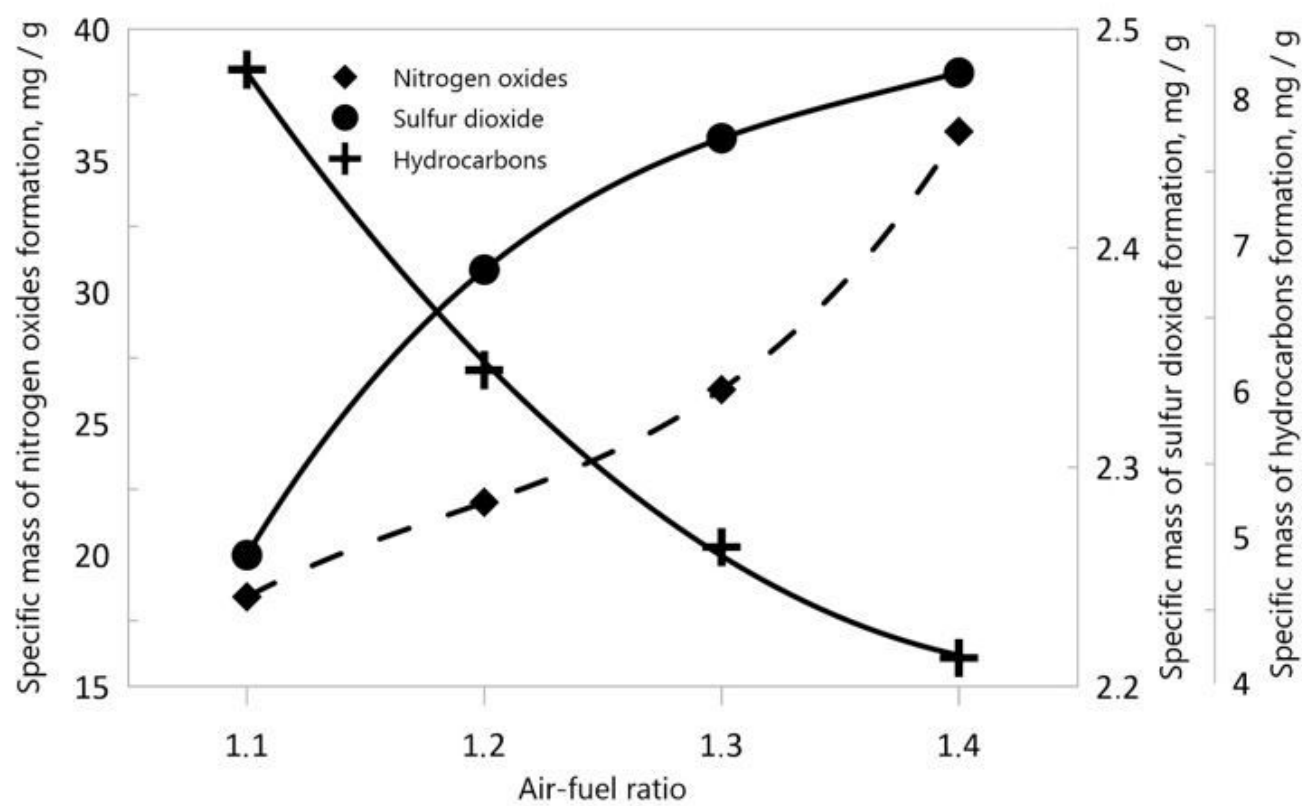


Figure 7

Effect of air-fuel ratio on the composition of waste gases

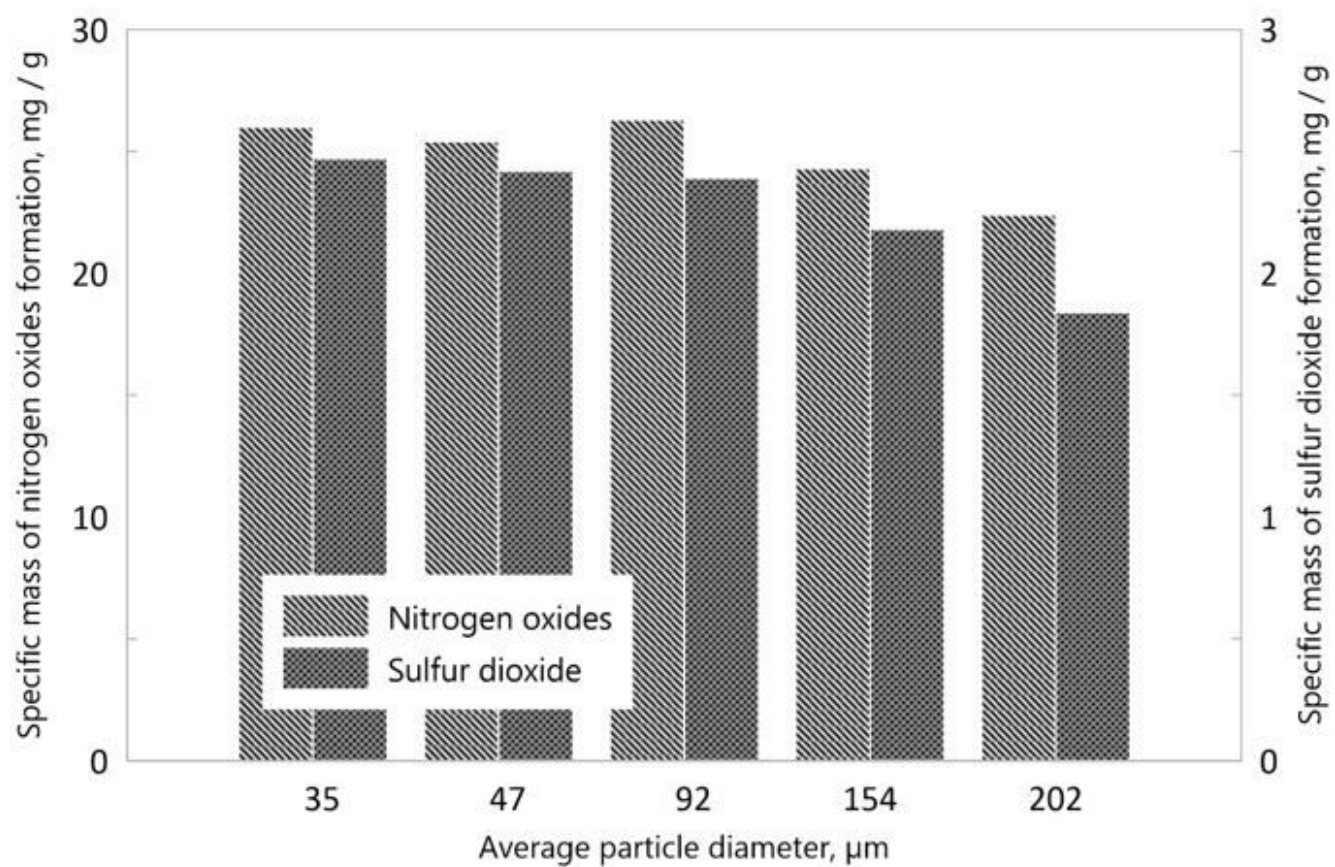


Figure 8

Influence of the suspension spraying degree on the waste gases composition