

## Features of Combustion of Water-fuel Emulsions with Different Methods of Introducing Water into the Combustion Zone

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**Abstract.** The main purpose of the article is to conduct research on combustion quality and determine nitrogen oxide concentrations for various methods of introducing water into the combustion chamber zone. To achieve the goal, the experimental study of combustion features was carried out on a combustion chamber model when supplying unwatered fuel oil of the M40 type, fuel oil, and water vapour in the amount equivalent to 30% of the mass of the fuel mixture, and two types of water-fuel emulsion with a water content of 15% and 30%. Values of gas temperature, concentration  $\text{CO}_2$ ,  $\text{H}_2$  and  $\text{CH}_4$ , as well as nitrogen oxides and ( $\text{NO}_2$ :  $\text{NO}$ ) ratio were measured along the length of the combustion chamber. Studies have shown a reduction in nitrogen oxide emissions and an increase in the ( $\text{NO}_2$ :  $\text{NO}$ ) ratio to 0,330 when supplying a water-fuel emulsion with a water content of up to 30%. This increases absorption properties of sulfuric acid in flue gases and reduces the intensity of low-temperature corrosion. When using a water-fuel emulsion of such a composition, it becomes possible to use condensation surfaces of boilers with a significant increase in their efficiency of up to 5 ... 9%. Experimental studies have also shown that additional generation  $\text{H}_2$ , significant thermal decomposition effect  $\text{NO}_x$ , generation of acoustic vibrations and microexplosions take place. This indicates that water-fuel emulsions are a special type of fuel, qualitatively and quantitatively changing the physicochemical processes of combustion. The most important results, constituting the significance of the research, are the experimental proofs of the advantage of using an innovative technology for preparing water-fuel emulsion, based on intense cavitation treatment of the fuel mixed with water obtained from an electro dialysis unit. This achieves better emulsion combustion performance compared to other methods of its preparation and the introduction of water into the combustion zone.

**Keywords:** water in the combustion zone, water fuel emulsion, microexplosions, thermal decomposition, acoustic vibrations.

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### Caracteristici ale arderii emulsiilor apă-combustibil cu diferite metode de introducere a apei în zona de ardere

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**Rezumat.** Scopul principal al articolului este de a efectua cercetări privind calitatea arderii și de a determina concentrațiile de oxid de azot pentru diferite metode de introducere a apei în zona camerei de ardere. Pentru a atinge obiectivul, studiul experimental al caracteristicilor de ardere a fost efectuat pe un model de cameră de ardere atunci când se furnizează păcură neadăpată de tip M40, păcură și vapori de apă în cantitate echivalentă cu 30% din masa amestecului de combustibil și două tipuri de emulsie apă-combustibil cu un conținut de apă de 15% și 30%. Valorile temperaturii gazului, concentrația  $\text{CO}$ ,  $\text{H}_2$  și  $\text{CH}_4$ , precum și oxizii de azot și raportul ( $\text{NO}_2$ : $\text{NO}$ ) au fost măsurate pe lungimea camerei de ardere. Cercetările au arătat că la furnizarea emulsiei apă-combustibil cu un conținut de apă de 30% se obțin cei mai buni indicatori de calitate a arderii în ceea ce privește valorile concentrației  $\text{CO}$ ,  $\text{H}_2$  și suma acestora în zona de ardere. Se stabilește reducerea nivelului de emisii de oxizi de azot și creșterea raportului ( $\text{NO}_2$ : $\text{NO}$ ) la 0,33. Aceasta mărește proprietățile de absorbție ale acidului sulfuric în gazele de ardere și reduce intensitatea coroziunii la temperatură joasă. Atunci când se utilizează o emulsie apă-combustibil dintr-o astfel de compoziție, devine posibilă utilizarea suprafețelor de condensare ale cazanelor cu o creștere semnificativă a eficienței lor de până la 5...9%. Studiile experimentale au mai arătat că are loc generarea suplimentară  $\text{H}_2$ , efect semnificativ de descompunere termică  $\text{NO}_x$ , generarea de vibrații acustice și microexplozii. Aceasta indică faptul că emulsiile apă-combustibil sunt un tip special de combustibil, modificând calitativ și cantitativ procesele fizico-chimice de ardere.

**Cuvinte-cheie:** apă în zona de ardere, emulsie apă-combustibil, microexplozii, descompunere termică, vibrații acustice.

### Особенности горения водотопливных эмульсий при различных способах ввода воды в зону горения

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**Аннотация.** Основной целью работы было проведение исследования качества сгорания и определение показателей концентраций окислов азота для различных методов ввода воды в зону камеры горения. Для достижения поставленной цели на модели камеры сгорания выполнено экспериментальное исследование особенностей горения при подаче необводненного мазута типа М40, мазута и водяного пара в количестве, эквивалентном 30% массы топливной смеси, и двух типов водотопливной эмульсии с водосодержащим 15% и 30%. Измерялись по длине камеры сгорания значения температуры газов, концентраций  $\text{CO}_2$ ,  $\text{H}_2$  та  $\text{CH}_4$ , а также оксиды азота и соотношение ( $\text{NO}_2:\text{NO}$ ). Исследованиями установлено снижение уровня выбросов окислов азота и повышение соотношения ( $\text{NO}_2:\text{NO}$ ) до 0,33 при подаче водотопливной эмульсии водосодержанием до 30%. Это повышает абсорбционные свойства серной кислоты в дымовых газах и снижает интенсивность низкотемпературной коррозии. При использовании водотопливной эмульсии такого состава возникает возможность использования конденсационных поверхностей котлов со значительным до 5...9% повышением их КПД. Экспериментальные исследования также показали, что имеет место дополнительная генерация  $\text{H}_2$ , значительный эффект термического разложения  $\text{NO}_x$ , генерация акустических колебаний и микровзрывов. Наиболее важными результатами, составляющими значимость проведенных исследований, являются экспериментальные доказательства преимущества использования инновационной технологии приготовления водотопливной эмульсии, основанной на жесткой кавитационной обработке топлива в смеси с водой, полученной в электродиализной установке. При этом достигаются лучшие показатели сгорания эмульсии по сравнению с другими способами её приготовления и введения воды в зону горения.

**Ключевые слова:** вода в зоне горения, водотопливная эмульсия, микровзрывы, термическое разложение, акустические колебания.

### INTRODUCTION

In order to solve the problems that have arisen, related to the increase in the cost of fuel, environmental protection, measures aimed at reducing the emission of harmful substances and increasing the efficiency of ship power plants at the same time are of great importance due to the improvement of combustion processes. Thermochemical methods are currently considered one of the most effective and economical methods of reducing nitrogen oxide concentrations in thermal power engineering. Water supply to the reaction zone is mainly carried out in two ways: by injecting steam or water into the air or the core of the torch, and by using water fuel emulsions (WFE).

### ANALYSIS OF THE LATEST RESEARCH AND PUBLICATIONS

Water-fuel emulsification is one of the proposed solutions that come under fuel upgradation strategies. This is indicated by the authors of the studies cited in works [1-4]. Except for a few contradictions, on a large scale, it has been observed that brake thermal efficiency increases and exhaust gas temperature decreases when the engine is run by water-diesel emulsified fuel. Brake-specific fuel consumption has shown a reducing trend if only diesel consumption is

considered as total fuel. The collective insight also reveals that water-fuel emulsion has great potential for the reduction of nitrogen oxides and smoke emissions in engines and steam boilers [5, 6]. From a larger perspective, the water-fuel emulsion has the potential of mitigating exhaust pollutions along with improving engines and boilers performance simultaneously [7-9].

According to published data [10-12], the accelerating effect of water vapour on the combustion process of carbon monoxide by the reaction  $\text{H}_2\text{O} + \text{CO} \rightarrow \text{CO}_2 + \text{H}_2$  leads to the appearance of flammable hydrogen. Further homogeneous oxidation of hydrogen leads to the formation of OH radicals and H and O atoms, which determine the development of the main reaction chains through processes, for example, ( $\text{OH} + \text{CO} \rightarrow \text{CO}_2 + \text{H}$ ). Therefore, hydrogen is oxidized completely after the oxidation of CO. The water introduced into the reaction zone plays not only the role of a coolant but also a chemical reagent, which is a source of active radicals OH- and  $\text{H}^+$ , which significantly affect the process of formation of NO and CO. Atomic oxygen formed at high temperatures in the presence of water vapour primarily reacts with  $\text{H}_2$  and carbon and much more heavily with  $\text{N}_2$ , so the concentration of atomic oxygen, which could participate in the formation of nitrogen oxides, decreases.

The articles [13, 14] are dedicated to mathematical modeling of the NO, N<sub>2</sub>O, and NO<sub>2</sub> generation in the flame zones with the temperature lower than 1700 K and in the presence of electrochemical effects, produced by the interaction of reaction flow with the electrical discharge. The main reaction mechanisms were investigated. There was discovered a link between HO<sub>2</sub> and H<sub>2</sub>O<sub>2</sub> production near the discharge domain and low temperature domain NO<sub>x</sub> generation. The additional electrochemical production of NO during various domain temperature and most important reagents concentration has been investigated.

In work [15] it is indicated that the thermochemical pre-flame preparation of hydrocarbon-hydrogen fuel allows to improve the environmental characteristics of its combustion due to the conversion of hydrocarbon fuel into a mixture of H<sub>2</sub> and CO, since the thermal decomposition of hydrocarbons in the flame with the formation active radicals CH, CH<sub>2</sub> is excluded, which fix atmospheric nitrogen. The analysis of the results of the calculations showed that the output of nitrogen oxides at a combustion temperature above 2000 K does not depend on the composition of the fuel. As the combustion temperature decreases, the output of nitrogen oxides varies more than 10 times, depending on the fuel composition. At the same time, it should be emphasized that the minimum output of NO occurs during the combustion of H<sub>2</sub>, CO, and their mixture, which is explained by the action of two competing mechanisms of NO formation: the thermal one, which prevails at temperatures above 2000 K, and the "fast mechanism" at temperatures 1800 K and less. At the same time, it is necessary to note the influence of the oscillatory mechanism of "fast" nitrogen oxidation in the flame front. Thus, when burning H<sub>2</sub> and CO or their mixture, the thermal mechanism of nitrogen oxidation is blocked. According to the authors, in the case of burning hydrocarbon fuel, it must be converted into a mixture of H<sub>2</sub> and CO during the pre-flame processes while simultaneously reducing the maximum temperature and oxygen concentration in the combustion zone and ensuring pre-flame low-temperature decomposition of the initial hydrocarbons, which also occurs during the combustion of WFE.

According to data [16], reducing NO<sub>x</sub> emissions is possible with the help of an adjustable composition (CO + H<sub>2</sub>). An increase

in the value of the sum (CO + H<sub>2</sub>) leads to a significant decrease in the NO<sub>x</sub> concentration. When the value of (CO + H<sub>2</sub>) approaches ~1.0 vol.%, the concentration of NO<sub>x</sub> decreases to the level of 150 mg/m<sup>3</sup>. When the concentration of (CO + H<sub>2</sub>) is reduced to ~ 0.02 mg/m<sup>3</sup>, the concentration of NO<sub>x</sub> increases when burning fuel oil to 900 mg/m<sup>3</sup>, which corresponds to the level of NO<sub>x</sub> emissions after an internal combustion engine [17].

In [18] it is noted that with pulsating fuel combustion in the combustion products significantly less nitrogen oxides, NO<sub>x</sub>, than during normal stationary combustion, due to the moderate combustion temperature of 1500...1700 K, the shorter reaction time of the fuel with oxygen, which is explained by oscillatory processes. It is important that during pulsating combustion, the time [τ<sub>NO<sub>x</sub></sub>] to reach the thermodynamically equilibrium concentration of NO is the leading factor because the time τ<sub>NO</sub> reaction is reduced by an order of magnitude compared to normal combustion. Decreasing the level of temperature in the combustion chamber by any method increases the equilibrium time [τ]<sub>NO</sub> reaction of NO formation. With a constant residence time of [τ]<sub>NO</sub> products in the high-temperature zone, the actual concentration of NO, which is proportional to the ratio τ<sub>NO</sub>/[τ]<sub>NO</sub>, will decrease not only due to a decrease in the equilibrium concentration NO, but also due to a decrease in the value of τ<sub>NO</sub>/[τ]<sub>NO</sub>.

Combustion of WFE as a result of micro-explosions takes place under the influence of significant and continuous anharmonic oscillations, and therefore the advantages of pulsating combustion also apply to the burning of water-fuel emulsions.

According to data [17], the technology of processing non-thermal gas cold plasma that allows simultaneous cleaning of gases from NO<sub>x</sub> and incomplete combustion products [19]. Despite the lack of knowledge on the kinetics of NO<sub>x</sub> transformation processes in cold plasma and the ambiguity of the relationship between the speed of these processes and energy consumption, [17] presented the results of research on a 5 kW diesel engine, which showed that the obtained degree of gas purification from NO<sub>x</sub> was 30 to 60%. Therefore, this result allowed the author to conclude that this technology is quite promising.

An important process that affects the final concentration of NO<sub>x</sub> at the exit from the combustion chamber (CC) is the thermal (under

the influence of changing gas temperature) decomposition of  $\text{NO}_x$ , which has already formed, to the CC section, where the conditions for reducing the gas temperature are ensured. According to the data [16], the efficiency of the thermal decomposition of nitrogen oxides formed in highly forced combustion chambers depends on the initial values of the gas temperature  $T_0$  and the concentration of nitrogen oxides  $\text{NO}_x$ , the gas cooling rate  $\phi$  and the temperature range of the gas temperature decrease  $\Delta T$ , in which the decomposition of the oxides occurs nitrogen. During the thermal decomposition of nitrogen oxides, their final concentration does not depend on the initial temperature and is determined only by the gas cooling rate  $\phi$ , which is facilitated by heat consumption for the dissociation process.

The article [20] gives the best results of using the phenomenon of cumulative impact to improve the spraying of fuel oil, emulsion and in the perspective of hydrocarbon suspensions in power boilers when cavitation is used. With severe cavitation, the flame of emulsion and fuel oil is characterized by stable combustion and dazzling white colour radiation. The authors came to the conclusion that in this flame there is dissociation of hydrocarbons and mineral particles with their further reaction and transition of reaction products to the initial state. That is, from the authors' point of view, a recombination process is taking place, which is observed during the plasma-change mode of combustion.

At the moment of a micro-explosion, a steam-air mixture with a large number of free electrons and ions is ejected in the jet; the process of combustion of WFE begins with the process of recombination of atomic hydrogen, which has significant reducing properties. When analyzing experimental data, it is necessary to take into account all factors that affect the output of  $\text{H}_2$ ,  $\text{CO}$ , and  $\text{CH}_4$ , as well as the output of  $\text{NO}_x$  and its components  $\text{NO}$  and  $\text{NO}_2$ , since their ratio in the composition of  $\text{NO}_x$  determines not only the level of toxicity of gases but also the level of their influence on the absorption properties of gases and the intensity of corrosion processes [21]. At the same time, it is necessary to take into account the impact on the output of  $\text{NO}_x$  processes associated with the passage of plasma processes during the combustion of WFE prepared in the mode of maximum cavitation preparation of WFE.

Steam gasification of carbon proceeds according to the main chemical reaction  $\text{C} +$

$\text{H}_2\text{O} = \text{CO} + \text{H}_2$ . In the process of plasma-steam conversion, there is a two-stage interaction of carbon with water vapour [12], and at the temperature of 1000 °C and above,  $\text{CO}_2$  is spent on the creation of  $\text{CO}$ , and the content of  $\text{CH}_4$  is less than 0.1%. In addition, the significant advantage of plasma-steam gasification over steam-air gasification is the absence of nitrogen oxides. The application is a high temperature of water vapour at a pressure close to atmospheric due to an increase in the total output of  $\text{CO}$  and  $\text{H}_2$  when the temperature of the gasification process increases.

The combustion of heavy oil and its emulsions with water in the fire-tube boilers were investigated in experiments on an industrial scale [21]. The performance of the fire-tube boilers, used in Tartous company for cement and construction materials, was studied when they were employed to be operated with heavy fuel oil and with the water phase of emulsified heavy oil containing 8 vol. % water and 92 vol. % heavy fuel oil. The emulsified water/heavy fuel oil with 8 vol. % of water content showed no separation and contained the smallest and most homogeneous droplets after stability tests. Four boilers, each with 8000 kg/h steam capacity, have been operated for 4 months with regular heavy fuel oil and water/heavy fuel oil. It has been found that the micro-explosion, observed in water/heavy fuel oil, improved the boiler efficiency and reduced the fuel consumption by 12.99%.

According to the authors of the article [23] water injection (WI) is a promising technology in diesel engines. However, the joint effects of WI and fuel injection strategy have not been investigated well. Furthermore, the comparison between WI and exhaust gas recirculation (EGR) requires further clarification. This study aims to identify the optimal way of WI and its benefits for a high-load diesel engine operated with various fuel injection strategies. Therefore, four schemes, i.e., diesel single injection strategy with/without WI and diesel double injection strategy with/without WI, were optimized by employing numerical simulation. The optimal water injection timing for the single injection strategy is near -108°CA ATDC, while it is 8...20°CA before the first diesel injection for the double injection strategy. Water mass is the most decisive parameter, and the optimal water masses are 10...35% and 29...51% of the fuel mass, respectively. When WI is employed alone without introducing EGR,  $\text{NO}_x$  can be reduced by 30% and 90%, respectively. Compared with EGR,

the main superiority of WI is reduced  $\text{NO}_x$  emissions without sacrificing fuel economy until the water mass reaches 50% of the fuel mass. For the single injection strategy, the cooling effect of WI is the dominant factor, while for the double injection strategy, the dilution effect becomes prominent.

The authors [24] presented the results of statistical significance tests for evaluating the main effect of water-diesel emulsion usage type E (containing 2, 5, 8, and 10% by vol.) and engine load on the engine performance and emission parameters. The decrease in heating value and increase in fuel density and viscosity were observed with increasing water content. Although the fuel pour point decreased with water presence, it didn't depend on water percentage. The combustion of emulsions significantly decreased the engine power and torque at the 1% probability level ( $P < 0.01$ ) due to the reduction in the heating value of emulsions. The lowest brake-specific fuel consumption was observed for E2. Generally higher brake thermal efficiency was found for emulsions due to more complete combustion. The significant decrease ( $P < 0.01$ ) in combustion temperature for E5, E8, and E10, increased the engine CO and decreased its  $\text{CO}_2$ . Emulsion usage decreased the engine  $\text{NO}_x$  through reducing combustion temperature when compared to neat diesel. As a whole, E5 with the highest improvement in the engine HC,  $\text{NO}_x$ , and  $\text{CO}_2$  could be the best suggestion to decrease undesirable engine emission.

## MATERIALS AND METHODS

The purpose of the work is to compare indicators of combustion quality and concentrations of nitrogen oxides with different methods of introducing water into the combustion zone.

The study of the effect of water vapour injection and combustion of water-fuel emulsions was carried out on an experimental setup, the general appearance and schematic diagram of which are shown in Fig. 1.

The setup is made in the form of an open-type aerodynamic stand and includes the following main functional elements: a combustion chamber equipped with a rotary nozzle device, a fuel preparation unit, a measuring unit, gas ducts, pumps, and blowers.

The water-fuel emulsion was prepared for combustion in the fuel preparation unit. Fuel oil M40 was used as the base, the consumption of which was  $(2.8... 8.4) \cdot 10^{-3}$  kg/s. The method of

dual-circuit rigid cavitation treatment was used to generate stabilized finely dispersed WFE. The size of water droplets in the emulsion was 1...2 mm; the hydrogen index pH was 8... 8.5. The description of features of WFE preparation is given in [22].

The experimental setup ensured the stability of parameters during combustion of both of M40 unwatered fuel oil ( $S^r = 1.8\%$ ,  $W^r = 2\%$ ) and during injection of water vapour to the torch root in an amount corresponding to 30% WFE, as well as during combustion of water-fuel emulsion based on this fuel oil with the water content of  $W^r$  equal to 15 and 30% at excess air coefficient values of 1.22...1.26.

All studies were performed using one portion of M40 fuel oil and water of constant quality used for water vapour injection and preparation of water-fuel emulsion. This ensured the same composition of the organic part of the WFE and increased the reliability of the obtained results.

The distribution of gas temperatures along the length and cross-section of the CC was determined with the help of a platinum-rhodium thermocouple, the working junction of which was placed at the gas inlet to the water-cooled probe. The accuracy of temperature measurements is  $\pm 5$  °C. With the help of the same probe, the isokinetic mode of gas sampling for composition analysis was ensured.

Control of the quality of combustion of fuel oil and WFE based on them was monitored using the Gasochrome-3101 chromatograph - measurement of the concentration of  $\text{H}_2$ , CO,  $\text{CH}_4$ ,  $\text{O}_2$  up to and including and the intersection of the CC for the purpose of determining the efficiency of combustion, evaluating non-burning products and determining the heat loss from chemical underburning.

A gas analyzer OKSI-5M was used to determine the concentration of  $\text{O}_2$  (and, accordingly, the coefficient of excess air  $\alpha$  during combustion), as well as the concentration of toxic emissions of  $\text{SO}_2$ ,  $\text{NO}_x$ , and separately NO and  $\text{NO}_2$ . The sensitivity threshold of gas analyzers (in vol.%) is at the following levels:  $5 \cdot 10^{-4}$  on  $\text{H}_2$ ;  $1 \cdot 10^{-3}$  on CO,  $\text{CH}_4$ ,  $\text{SO}_2$  and  $\text{NO}_x$ ;  $2 \cdot 10^{-2}$  on  $\text{O}_2$ . The relative error is  $\pm 5\%$ .

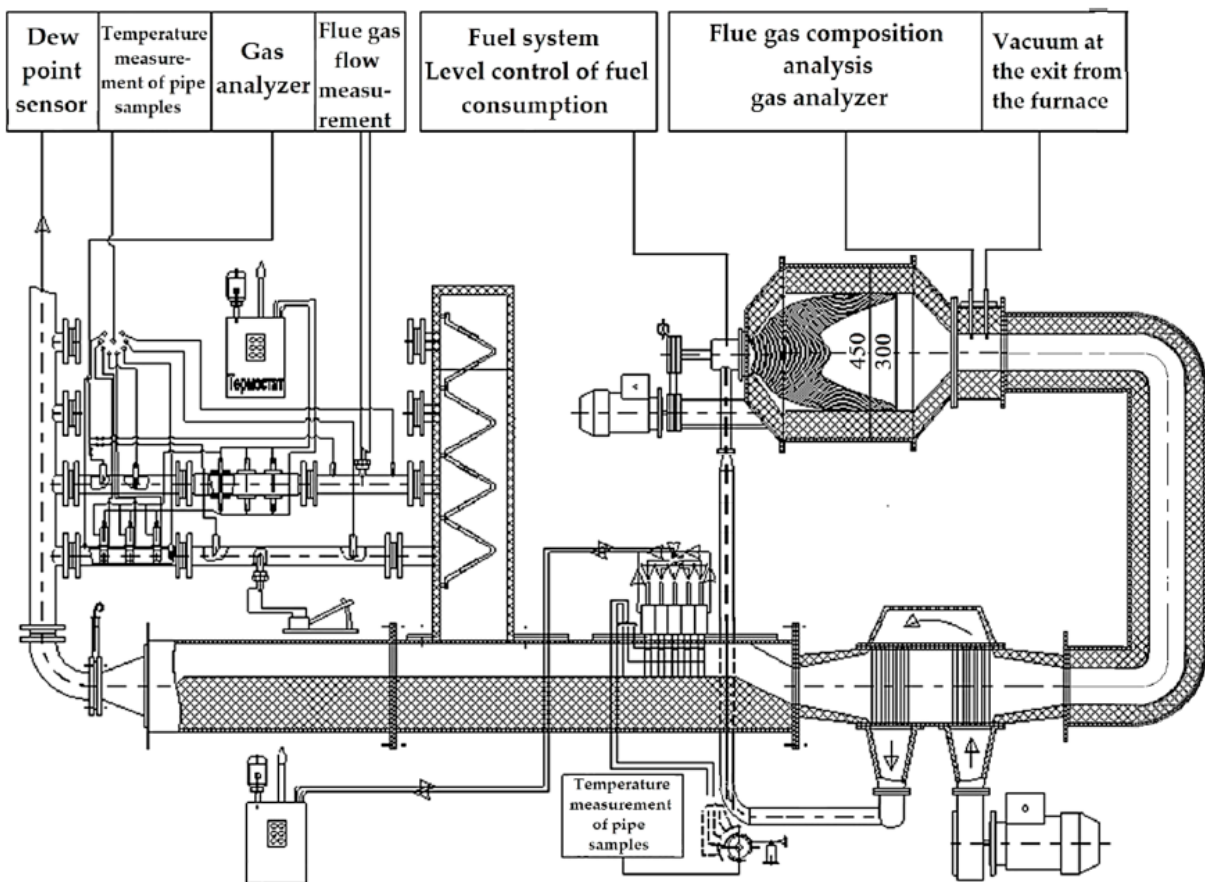


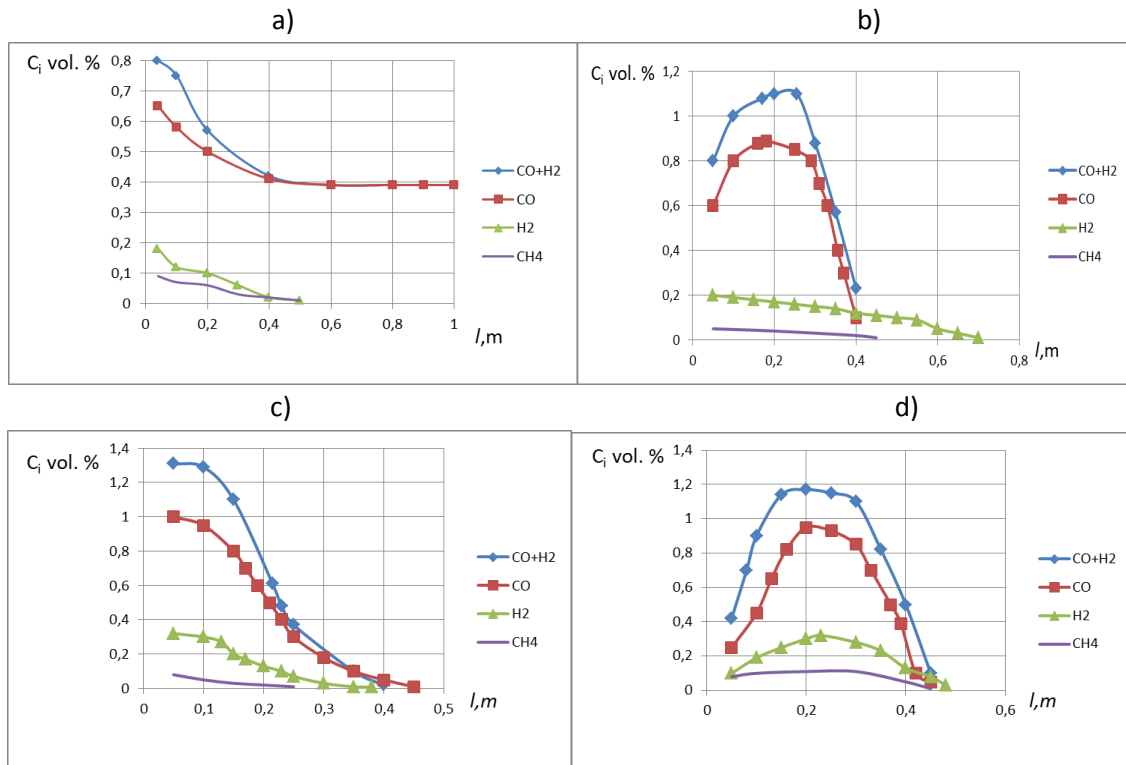
Fig.1. The schematic diagram and general view of the experimental setup.

### RESULTS AND DISCUSSION

The results of the study of the quality of WFE combustion and the change in the process temperature along the length of the combustion chamber are presented in Fig. 2 and Fig. 3.

When burning fuel oil (Fig. 2, a), the lowest concentrations of  $H_2$  and  $CO$  and their sums were obtained  $CO + H_2$  from all considered regimes. Moreover, the concentration of  $CO$  changes little

along the length of the CC. Apparently due to the insufficient amount of  $H_2$  and  $H_2O$ , which slows down the course of oxidation reactions of  $CO$  to  $CO_2$ , despite the lower value of the maximum gas temperature as shown in Fig.3, is equal to  $1855^{\circ}C$ , which should reduce the concentration of  $NO_x$ . The minimal effect of reducing properties ( $CO + H_2$ ) contributes to the increase of  $NO_x$  concentration to the maximum value of  $532 \text{ mg/m}^3$ .



**Fig. 2. The concentration of gases along the length of the combustion chamber for the modes: a - during combustion of M40 fuel oil; b - with injection of water vapour into the combustion zone equivalently to 30% of the WFE; c - during combustion of WFE with  $W^r = 15\%$ ; d - during combustion of WFE with  $W^r = 30\%$ .**

At the same time, it is necessary to take into account the lack of influence of factors that lead to the decrease in  $\text{NO}_x$  emissions, which appear during the combustion of WFE.

As a result of the lower efficiency of the pre-flame processes (especially, the processes of mixture formation), the maximum gas temperature  $T$  is located in the intersection located at 0.4 of the CC length. At the exit from the CC, the concentrations of CO,  $\text{CH}_4$ , and  $\text{H}_2$  are relatively high, which leads to an increase in heat loss from chemical underburning at the level of 1%. At the same time, the value of the  $(\text{NO}_2:\text{NO})$  ratio, equal to 0.143, is the smallest of the considered regimes, which does not ensure passivation of heating surfaces with a wall temperature lower than  $130^\circ\text{C}$ . In this regard, there is an increase in low-temperature acid corrosion with the appearance of a "peak" at the level of 1,2 mm/year at the temperature of the wall of about  $110^\circ\text{C}$ , which limits the temperature of waste gases at the level of  $150\text{--}160^\circ\text{C}$  [22]. Therefore, when burning sulfur fuel oil, the efficiency of auxiliary boilers is below 85 %, as well as the limited depth of gas heat utilization.

When injecting the amount of water vapour equivalent to 30% of the WFE (Fig. 2, b),

the concentration of  $\text{H}_2$  and CO and their amount increases, and the maximum temperature of gases decreases to  $1820^\circ\text{C}$  (Fig. 3). Therefore, under the influence of these two factors, the concentration of  $\text{NO}_x$  decreases by 1.33 times compared to the burning of fuel oil, and the value of the  $(\text{NO}_2:\text{NO})$  ratio increases to 0.268. As a result of the improvement of the combustion process, the maximum gas temperature is located closer to the burner section.

However, due to the lack of influence of factors inherent in the combustion process of WFE (micro-explosions, plasma mode, anharmonic acoustic field, reductive properties of hydrogen atoms), the level of WFE combustion modes is not reached.

When burning WFE with  $W^r = 15\%$  (Fig. 2, c), the quality of combustion is higher. The maximum concentrations of CO and  $\text{H}_2$ , therefore CO +  $\text{H}_2$  are higher and located at the closest distance from the burner cut ( $\sim 70$  mm) from all the modes considered due to the excess of the amount of heat released over the heat consumption of the gases for the evaporation of the WFE water and its pyrolysis.

The maximum temperature of gases is located at the relative distance of 0,07 of the CC length and

reaches 1950 °C (Fig. 3), which should lead to an increase in the concentration of NO<sub>x</sub>.

However, due to the greater influence of the reducing properties of the increased amount (CO + H<sub>2</sub>), the concentration of NO<sub>x</sub> decreases.

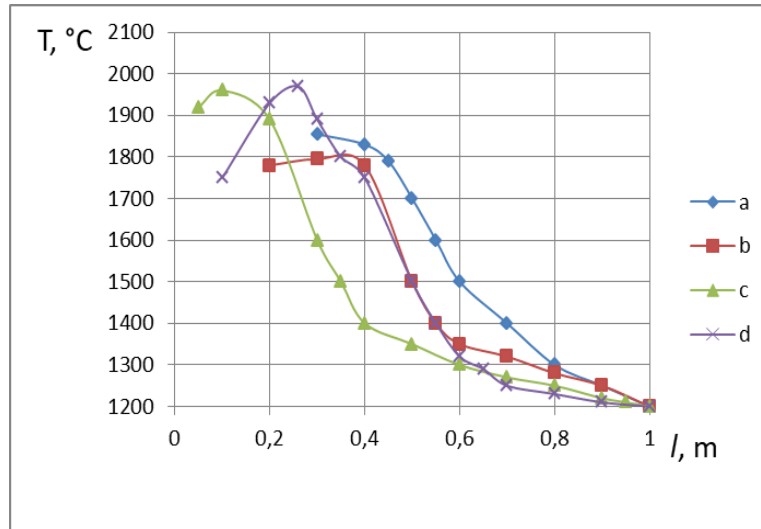


Fig. 3. The temperature of gases along the length of the combustion chamber for combustion modes a, b, c, and d (designations according to Fig. 2).

During the combustion of WFE, conditions are created for the passage of micro-explosions of its droplets and the plasma combustion mechanism, in addition, the strong reducing properties of H<sub>1</sub>' hydrogen atoms, accompanied by recombination reactions with the release of heat at the level of 400 MJ/mol and the instant increase in the temperature of up to 4000...10000 °C, which then sharply decreases due to heat consumption for endothermic dissociation reactions.

Then, under the influence of micro-explosions, after vigorous mixing of the recombination products with another flow of combustion products, the average temperature of the gases is established with the maximum value of 1950 °C. In this local area, the first stage of thermal decomposition of NO<sub>x</sub> occurs at the rate of 107 K/s [16]. This is followed by the second section of the sharp decrease in the gas temperature to 1600 °C due to the high rates of combustion reactions and the consumption of the certain amount of heat for the dissociation reactions of CO<sub>2</sub> and H<sub>2</sub>O, as well as intense radiant heat exchange.

According to data of [16], under the influence of reducing properties (CO + H<sub>2</sub>), the process of thermal decomposition of NO<sub>x</sub> takes place at the lower speed at the level of 105...103 K/s. In the next section of the CC when the temperature of the gases decreases from 1600 °C to 1200 °C at

the exit of gases from the CC, the process of thermal decomposition of NO<sub>x</sub> practically stops.

Setting the ratio of the reaction time to the time of reaching the equilibrium concentration of NO<sub>x</sub>, which is significantly smaller due to the increase in the speed of reactions under the influence of acoustic anharmonic oscillations (by analogy with processes of pulsating combustion), as well as the effect of the increase in the amount of concentration (CO + H<sub>2</sub>) on binding N<sub>2</sub> of air by active radicals CH and CH<sub>2</sub> [15].

Thus, in connection with the specified simultaneous passage of four mechanisms (reductive properties of H<sub>1</sub>' hydrogen atoms during recombination reactions, the influence of reductive properties of the total concentration (CO + H<sub>2</sub>) of thermal decomposition and the influence of anharmonic acoustic field) the concentration of NO decreases in comparison with the considered regimes to the level of 270 mg/m<sup>3</sup>, i.e. 2.0 times in comparison with the fuel oil burning regime and 1.5 times in comparison with the regime introduction of water vapour. The absolute amount of NO<sub>2</sub> in NO<sub>x</sub> decreases but the (NO<sub>2</sub>: NO) ratio increases to 0.3.

When burning WFE with W<sup>r</sup> = 30% (Fig. 2, d), the maximum concentrations of CO, H<sub>2</sub>, (CO + H<sub>2</sub>) and gas temperature move by a distance up to

200 mm from the burner cut (0.2 of the CC length). The level of maximum concentrations is practically at the level of the combustion regime with  $W^r = 15\%$  but the completion of combustion reactions and the creation of  $\text{NO}_x$  at the temperature of  $1600\text{ }^\circ\text{C}$  (Fig. 3) ends at the distance that is almost 2 times greater.

As a result of the influence of the four mentioned mechanisms of combustion of WFE, the  $\text{NO}_x$  concentration decreases to  $166\text{ mg/m}^3$ , i.e. 1.6 times less compared to the  $W^r = 15\%$  mode. The absolute amount of  $\text{NO}_2$  in  $\text{NO}_x$  decreases, and the  $(\text{NO}_2:\text{NO})$  ratio increases to 0.33, which leads to the increase in the absorption properties of flue gases, the increase in the concentration of  $\text{NO}$  in the  $\text{H}_2\text{SO}_4$  condensate on the condensing heating surfaces with wall temperatures of  $130\text{--}70\text{ }^\circ\text{C}$ , which provides the passivation of the surface of carbon steel with nitrogen oxides and, as a result, the significant reduction of low-temperature acid corrosion to the level of  $\sim 0.15\text{--}0.3\text{ mm/year}$  [22].

The decrease in  $\text{NO}_x$  concentration compared to the regime of  $W^r = 15\%$  is explained by increasing the duration of the effect of the total concentration  $(\text{CO} + \text{H}_2)$  on  $\text{NO}_x$  formation processes (up to the temperature of  $1600\text{ }^\circ\text{C}$ ) by almost 2 times.

The temperature difference of the gases, the duration of the thermal decomposition process, formed during the combustion of  $\text{NO}_x$ , is almost the same as the  $W^r = 15\%$  mode (occurs on the 0.2 m long CC section only shifted by  $\sim 0.2\text{ m}$  from the burner section). Since the dispersity and activity of WFE at the regimes of  $W^r = 15\%$  and  $W^r = 30\%$  were provided almost the same, then the influence of the level of sound field energy on the creation of  $\text{NO}$  should be taken as large due to the higher content of active water in the composition of WFE.

Comparison of the effect of the sum  $(\text{CO} + \text{H}_2)$  on the length of the CC when burning WFE with the water content of 15 and 30% (with practically the same maximum concentration at the level of  $\sim 1.2\text{ vol.}\%$  but different quantity in flow  $(\text{CO} + \text{H}_2)$  along the length of the short circuit, determined by the area under the curves  $(\text{CO} + \text{H}_2)$  at  $W^r = 15\%$  and  $W^r = 30\%$ ) showed that at the water content of  $W^r = 30\%$  the influence of  $(\text{CO} + \text{H}_2)$  should be almost 1.7 times more. Therefore, the concentration of  $\text{NO}_x$  should decrease in the same proportion.

According to the experimental data as shown in Fig. 4, the  $\text{NO}_x$  concentration at  $W^r = 30\%$  is  $166\text{ mg/m}^3$ , and at  $W^r = 15\%$  –  $270\text{ mg/m}^3$ , i.e. at  $W^r = 30\%$ , the  $\text{NO}_x$  concentration is 1.62 times less, which can be explained by the higher reducing activity of  $\text{H}_1$  and hydrogen atoms  $(\text{CO} + \text{H}_2)$ , the higher efficiency of thermal decomposition of nitrogen oxides and the higher efficiency of the impact of acoustic field energy at  $W^r = 15\%$ . Since the maximum values of gas temperatures  $1950\text{ }^\circ\text{C}$  at  $W^r = 15\%$  and  $1940\text{ }^\circ\text{C}$  at  $W^r = 30\%$ , then apparently the acoustic field has a greater influence on reducing reaction time  $\tau_{\text{NO}}$  to time reaching the equilibrium state  $[\tau]_{\text{NO}}$ .

The sequential comparison of the mentioned regimes in comparison with the burning of fuel oil (Fig. 2, a) shows that: when injecting water vapour to the root of the torch (Fig. 2, b) the concentration of  $\text{NO}_x$  is reduced by 1.33 times ( $\text{NO}$  decreases by 1.48 times, and  $\text{NO}_2$  increases by 1.27 times,  $(\text{NO}_2:\text{NO})$  increases by 1.87 times).

When burning WFE with  $W^r = 15\%$  (Fig. 2, c) the concentration of  $\text{NO}_x$  decreases by 1.9 times ( $\text{NO}$  by 2.33 times,  $\text{NO}_2$  increases by 1.1 times and  $(\text{NO}_2:\text{NO})$  increases by 2.1 times); when burning WFE with  $W^r = 30\%$  (Fig. 2, d), the  $\text{NO}_x$  concentration decreases by 3.2 times ( $\text{NO}$  by 3.7 times,  $\text{NO}_2$  increases by 1.6 times, and  $(\text{NO}_2:\text{NO})$  increases by 2.3 times).

Comparison of the data on changes in the concentration of  $\text{NO}_x$  and its constituents  $\text{NO}$  and  $\text{NO}_2$  along the length of the combustion chamber (Fig. 4) shows that in all combustion modes (consecutively during the injection of water vapour to the root of the torch in the amount at the level of 30% emulsion, combustion of WFE with  $W^r = 15\%$  and  $W^r = 30\%$ ) the significant decrease in the concentration of  $\text{NO}$  and  $\text{NO}_x$  is observed.

It is important to note that the ratio of  $(\text{NO}_2:\text{NO})$  at the outlet of the CC increases from 0.143 when burning fuel oil to 0.33 when burning WFE with  $W^r = 30\%$  (since this ratio is close to equimolar, the absorption properties of flue gases improve (which is important when applying scrubbing technologies) and their corrosion properties (which contributes to the passivation of carbon steels due to more effective absorption of nitrogen oxides), which leads to the decrease in the intensity of low-temperature acid corrosion [22].

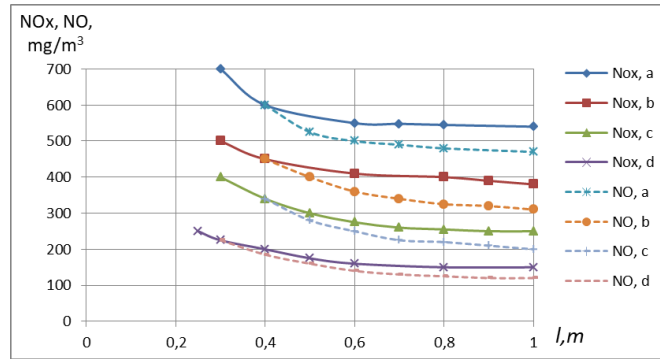


Fig. 4. The concentration of nitrogen oxides along the length of the combustion chamber.

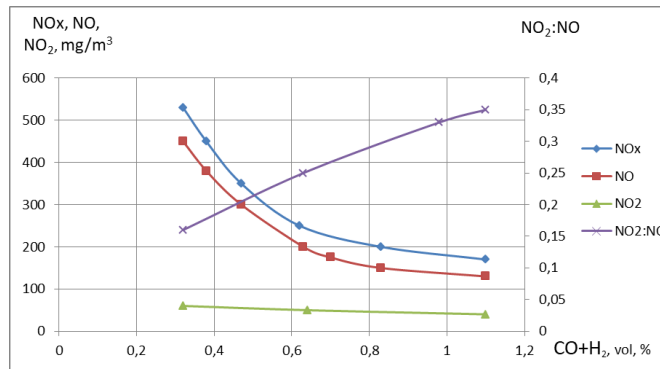


Fig. 5. The concentration of nitrogen oxides and the (NO<sub>2</sub>:NO) ratio from the (CO + H<sub>2</sub>) concentration.

According to the obtained approximation equation of the dependence of (NO<sub>2</sub>:NO) on the sum of (CO+H<sub>2</sub>) (Fig. 5) the equimolar ratio of (NO<sub>2</sub>:NO) can be obtained when the value of (CO+H<sub>2</sub>) is reached at the level of 1.8 vol.%. This can be ensured by increasing the intensity of the cavitation-circulation preparation of the WFE using the electro dialysis method for the preparation of fresh water (dilute). With such processing, in water under the action of an electric field, an additional accumulation of free electrons and ions occurs, which contribute to the intensification of the plasma mode during the combustion of the emulsion.

### CONCLUSIONS

1. Distributions of concentrations of CO, H<sub>2</sub>, CH<sub>4</sub> combustion products, as well as nitrogen oxides along the length of the combustion chamber depending on the method of introducing water into the combustion chamber were obtained on the experimental setup.

The studies were carried out with the supply of non-watered M40 fuel oil, two types of water-fuel emulsion with a water content of  $W^r = 15\%$  and  $30\%$ , respectively, and also with the supply of water (water vapor) into the combustion chamber in an amount equivalent to a  $W^r = 30\%$  emulsion. The obtained results can be used to

evaluate the effectiveness of various methods of introducing water into the combustion chambers of boiler units and heat engines.

2. It has been experimentally established that in comparative tests of  $W^r = 30\%$  emulsion and when M40 fuel oil is injecting into the combustion zone separately with the amount of water vapour equivalent to  $30\%$  of the WFE, the efficiency and quality of emulsion combustion are higher. It is also established that the emulsion combustion process is localized on a shorter section along the length of the combustion chamber.

3. A comparison of the combustion processes of liquid fuels with different methods of water vapor injection into the combustion zone showed that with an increase in the amount of injected water from  $2\%$  when burning fuel oil to  $30\%$  when burning a water-fuel emulsion with a water content of  $W^r = 30\%$ , the quality of combustion improves: the concentration of CO increases and H<sub>2</sub> in the process of pyro-genetic reactions and the concentration of nitrogen oxides decreases.

4. Compared to the value of the concentration of Nox equal to  $532 \text{ mg/m}^3$ , obtained for fuel oil with a water content of  $2\%$ , there is a significant reduction of nitrogen oxides during the combustion of water-fuel emulsions of  $W^r = 15\%$  and  $W^r = 30\%$  in 2 and 3.2 times, respectively. This increases the ecological

indicators of combustion chambers of boiler units and reduces the level of emissions of toxic nitrogen oxides into the environment when using water-fuel emulsions with a high water content.

5. The increase in the quality of combustion during the burning of emulsions is explained by the fact that during the burning of the emulsion under the action of micro explosions of its droplets, the concentration of (CO+H<sub>2</sub>) and atoms increases hydrogen with significant reducing properties, conditions for the thermal decomposition of nitrogen oxides improve, and the intensity of acoustic vibrations increases

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