EXPERIMENTAL RESEARCHES OF THE EFFECT OF VEGETABLE OIL ADDITION ON THE EMISSIONS CHARACTERISTICS DURING COMBUSTION OF COAL LIQUID FUELS

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This paper presents the findings of research into combustion of vegetable oils in the composition of coal liquid fuel. The aim of the research was to studies the influence of additives of typical vegetable oils (rapeseed, olive, coconut oil, etc.) on concentrations of anthropogenic emissions during combustion of coal water slurries based on coal processing waste. In order to study the effect of different parameters on the emissions efficiency, the tests were done in different operating conditions: muffle furnace temperature, share of oil (up to 15%) in the mixtures and oil type. The differences between the concentrations of sulfur and nitrogen oxides in the combustion of typical filter cakes (waste coal), as well as those of suspensions with the addition of vegetable impurities have been investigated. It is shown that the concentrations of SO_x *can be reduced by 5–63% and those of* NO_x *– by 5–62% in comparison with coal liquid fuels based on oil refinery waste. Using the generalizing criterion, the paper illustrates the advantages of adding vegetable oils to enhance the prospects of slurry fuels (even based on waste coals) in comparison with coal that is the most dangerous in terms of environmental pollution.*

Keywords: *coal liquid fuels, additives, vegetable oils, combustion, anthropogenic emissions, comprehensive criterion.*

1. Introduction

1.1. The role of coal and slurry fuels

Solid fuel (coal) is the main fuel in the production of electric power [1, 2]. It accounts for 41% of the world's electricity. Coal reserves were discovered in 106 countries of the world (Fig. 1) [3]. However the future of coal power poses many uncertainties related to the implementation of national and international policies to support the use of renewable and alternative energy sources, to improve energy efficiency and to reduce emissions of carbon dioxide. It is not unreasonable to predict that in 30 years coal will still be the main resource for electricity generation, providing more than 30% [3] of electricity generation in the world. According to the forecast of the International Energy Agency [3], by the year 2040 coal consumption in the world will have reached almost 5.5 billion tons, i.e. 0.8 billion tons or 18% more than the currently consumed volume. The volume of international coal trade will increase significantly. In 2040, 1.1 billion tons of coal will be supplied to the international market for combustion in power plants and other enterprises of importing countries [3].

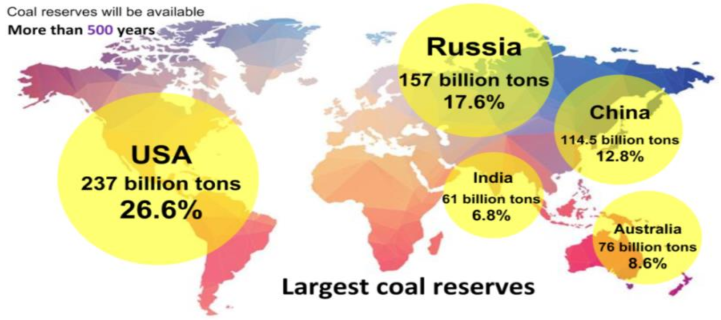


Figure 1. Coal reserves volumes by countries of the world [3]

Currently, coal is also considered as one of the ways to obtain liquid fuel. On its basis, as well as based on coal preparation wastes, coal-water and coal-water fuels containing petrochemical are created [4, 5]. China is the world leader in the development and introduction of coal-water compositions in the fuel and energy complex [4, 6]. Researchers from Japan, the USA, Canada, Italy and Russia are also making their practical and scientific contribution to the implementation of coal-water technologies [4-7]. Coal-water slurries (CWS) (or coal liquid fuels (CLF)) is a dispersed system (water, ground coal, chemical additives and impurities), in which energy and non-energy coals are usually used as a combustible basis. In addition, [5, 7] coal sludge and screenings, waste of coal-processing plants (filter-cakes), low-grade coal, and solid residual products of processing of traditional energy resources (coal, oil) may be used [5, 7-9]. The introduction of CWS ensures the preservation of energy and material resources, as well as the environment [8]. In addition, the use of CLF is the most effective and environmentally friendly method of utilization of thin coal sludge of coal mining and coal processing plants [5, 7]. One of the possible directions of development of CWF application technologies is transition to coal-based fuel compositions with addition of typical oil refining wastes. Such fuels are called coal-water slurries containing petrochemicals (CWSP) or composite fuels, which on their calorific value become comparable to traditional coals and eliminate the problem of low combustion temperatures of CWS.

Particularly active efforts to reduce the negative impact of industrial activities on climate change have been made over the past 30 to 50 years (The Kyoto Protocol adopted in 1997 in Kyoto, Japan). One of the promising directions for today is the involvement of plant components in the processes of energy generation. The known works [10-24] are devoted to co-combustion of coal with all sorts of biological additives. As additives to coal fuels are used waste wood (sawdust, chips) [11, 12], straw [13], vegetable oils (e.g. sunflower and olive oils) [14, 15], olive cake [16, 17], fruits stone [18], coconut shell [19], sunflower husk [20, 21], rapeseed oil [22], glycerol [23], rice husk [24]. The processes of preparation, ignition, combustion, and formation of gaseous emissions and ash have been considered at co-combustion of coal and biomass (with varying mass fractions of each component of the mixture). The vast majority of the results indicate a significant reduction in the amount of emissions due to the involvement of plant additives in the process of energy generation [10-24]. However, much less works aim at studying the combustion processes of composite liquid fuels with an admixture of a vegetable component. The main interest is a comprehensive experimental study of energy, technical, economic and environmental indicators of combustion fuels based on industrial waste and promising additives of vegetable origin, primarily vegetable oils and their processing waste.

1.2. Vegetable oils

Vegetable oils are energy sources that represent not only a productive alternative for agriculture, but also an important step towards ecological energy supply [25]. The source of vegetable oils is oil plants, containing vegetable fats in their various parts. Vegetable oils are characterized by a minimum content of sulfur and polycyclic aromatic hydrocarbons, high cetane number, and high flash point. They are nontoxic, bio-degradable, non-polluting and well mixed with liquid fuels [26-28]. The high cetane number (e.g. 42 for palm oil) helps to reduce the ignition delay period. The increased flash temperature provides high fire safety.

The total volume of production of major vegetable oils in the world in the 2015/16 season amounted to 178.3 million tons. In 2017–2018, production volumes are expected to grow by 3%, up to 184 million tons (Fig. 2). According to the OECD forecast, the total volume of vegetable oil production in 2025 will grow almost to 220 million tons (by more than 20%) [26, 29].

Vegetable oils are renewable, available and environmentally energy resources, which due to their valuable characteristics can be used for different purposes. For example, the possibility of using vegetable oils for biodiesel production [27, 30, 31] is being actively investigated. However, at present vegetable oils are mainly applied in the food industry. Worldwide, large amount of oils are used for processing food, which in turn leads to the oils waste production that must be biologically degraded before removal. So these wastes are considered as a raw material for the production of hydrocarbon fuels by catalytic pyrolysis [32], and also as biodiesel feedstock [33]. Recently, waste olive and sunflower oils of household origin have been successfully employed in our as agglomerates to recover coal from coal processing wastes [34].

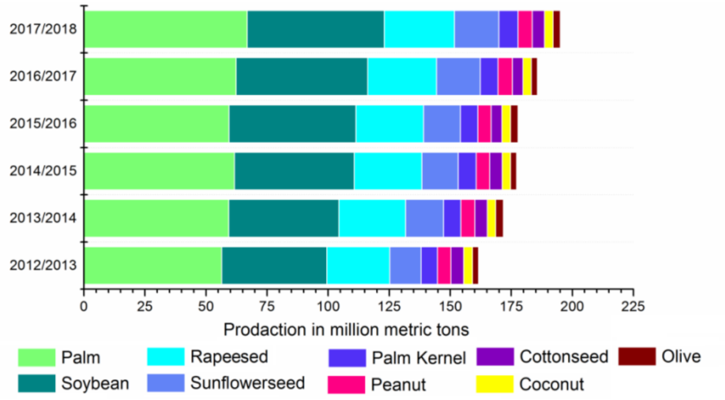


Figure 2. Production of major vegetable oils worldwide from 2012/13 to 2017/2018, by type (in million metric tons) [29]

1.3. Research goals and objectives

Preliminary studies [8, 35] allowed determining significant ecological advantages of CWF and CWSP based on coals of different brands, wastes and products of their processing in comparison with coals of different brands. In particular, the main anthropogenic emissions (sulphur and nitrogen oxides) can be significantly reduced (20–40%). [8, 35]. The use of CWSP at coal-fired thermal power plants and boiler houses can solve a group of important problems [5, 7, 8], for example, disposing numerous industrial wastes and releasing large areas occupied by them; expanding the raw material base of thermal plants; lowering the emperature regime of slurry burning in furnace chambers and extending the fleet life of thermal power equipment; as well as reducing the formation of anthropogenic emissions. To increase the combustion heat and the shelf life as well as to optimize the cost of transportation, the combustible, lubricating and flammable materials are added to the CLF suspensions; this obviously leads to a certain increase in the concentrations of anthropogenic emissions. By means of specialized impurities and additives to CWSP, the concentration of NO_x and SO_x can be significantly changed. Within the framework of this work, it is planned to study the influence of vegetable oils in the composition of the investigated suspensions, which can potentially have a significant positive impact on the environmental indicators of fuel combustion.

The aim of this work is to experimentally determine the influence of typical vegetable oils on the concentrations of anthropogenic emissions in the combustion of suspension coal fuels prepared on the basis of coal preparation and oil refining wastes. The study of the ecological characteristics of the combustion of CLF with vegetable oils has a worldwide significance. Countries such as Indonesia, Malaysia, the Philippines, India, which have great agrarian potential but not have enough traditional energy resources, may in the future replace part of the supplied coal or gas with their own bioenergy resources. This will help reduce dependence on energy imports, the development of the country's economy, and the preservation of the environment. Due to their properties and production volumes, vegetable oils used as additives to aqueous fuels are of interest within this study.

2. The study of environmental indicators of CWSP application

2.1. Materials

A typical waste of coal preparation plants, i.e. filter-cake (based on stone coking coal) is considered. The formation of this type of waste is provided in the course of coal washing with water using surfactants. After separation of the coal fractions, the wash water is supplied to a special container, where the sedimentation of coal particles occurs. The wet residue of coal and water is filter cake. The average size of the coal dust particles in the filter cake was no more than 100 microns. Table 1 presents the results of the technical and elemental analysis of the studied waste. For the preparation of CWSP based on filter cake the waste turbine oil was used (Tab. 2) provides the main characteristics of these components. The list and main properties of vegetable supplements are given in Tab. 3.

Table 1. Elemental and technical analysis of the solid fuel component

Grade of coal	Water fraction, %	A^d, %	V^{daf}, %	$Q^a_{s,V}$, MJ/kg	C^{daf}, %	H^{daf}, %	N^{daf}, %	S_t^d, %	O^{daf}, %
Filter cake of coking coal (C)	43.5	26.46	23.08	24.83	87.20	5.09	2.05	1.022	4.46

Table 2. Results of the analysis of characteristics of liquid fuel component

Component	ρ at 20 °C, kg/m^3	W^a, %	A^d, %	T_f, °C	T_{ign}, °C	$Q^a_{s,V}$, MJ/kg
Waste turbine oil	868	–	0.03	175	193	45.1

Table 3. Properties of vegetable oils [30, 36-39]

Physicochemical characteristics	Oil					
	Rapeseed [37]	Olive [38]	Coconut [36]	Palm [36]	Soybean [38, 39]	Sunflower [30, 38]
ρ at 15 °C, kg/m^3	921	925	879	923	925	920
Viscosity at 40 ˚C, мм^2/s	35.1	32	25.1	38.5	32	34
Cetane number	38	39	43	42	38	37
Heat combustion, MJ/kg	39.2	39.4	39.38	37.85	39.6	39.6
Flash point, ˚C	225	210	215	235	225	225
Freezing point, ˚C	-4…-10	-2…-6	+19…+26	+31…+41	-8…-18	-16…-19

Mass fraction of moisture and volatile, % no more	0.1…0.3	0.1…0.3	0.15…0.2	0.05…0.3	0.1…0.3	0.1…0.3
Mass fraction, % S C H O N	 0.03 79.6 11.4 8.97 0	 0 – – – –	 0 75.30 12.38 12.32 0	 0 75.3 11.75 12.95 0	 0 76.71 10.64 12.65 0	 0.03 77.68 12.25 9.8 0.24
Cost (C_i), $/kg	0.8	4.2	1.2	0.58	0.7	0.7

Based on the data of tab. 3, all oils have similar physical and chemical properties, so it is impractical to consider each type of oil. Rapeseed oil, olive oil and coconut oil were chosen to determine the extent of the impact of the vegetable oil addition to CWSP on environmental (concentrations of anthropogenic emissions), energy (heat of combustion) and economic (cost of fuel) indicators.

2.2. Methodologies for preparing fuels and research methods

The preparation of the CWSP under study was carried out using homogenizer (disperser) MPW-302 [8]. According to the required relative mass concentration, water and vegetable oil were mixed. The duration of the mixing of the components of the water-oil emulsion was 3-4 minutes. Then a coal component (filter cake) was introduced into the resulting emulsion. The duration of this mixing stage was 8-10 minutes. On average, the relative mass concentration of the coal component (filter cake) varied from 85 to 100 %, and that of the liquid fuel component – within 0–15 %.

The stand presented in Fig. 3 was used for the analysis of concentrations of the gaseous emissions, formed at burning of coals, waste of coal enrichment, as well as perspective CLF and CWSP. The main elements of the experimental setup are the combustion chamber, which is a tubular muffle furnace, and a gas analyzer. Application of muffle furnace allows creating an air environment with a wide range of temperatures (700-1,000 °C).

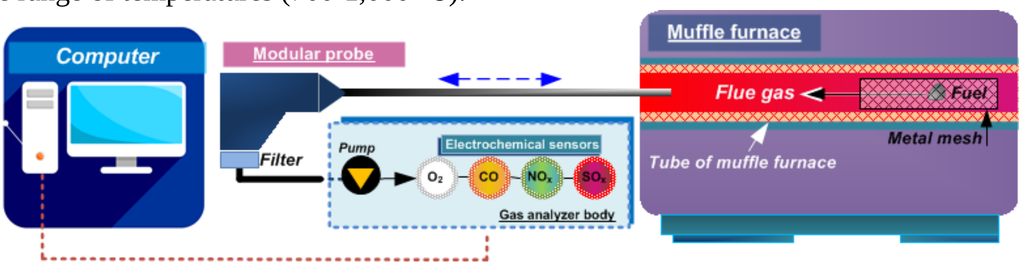


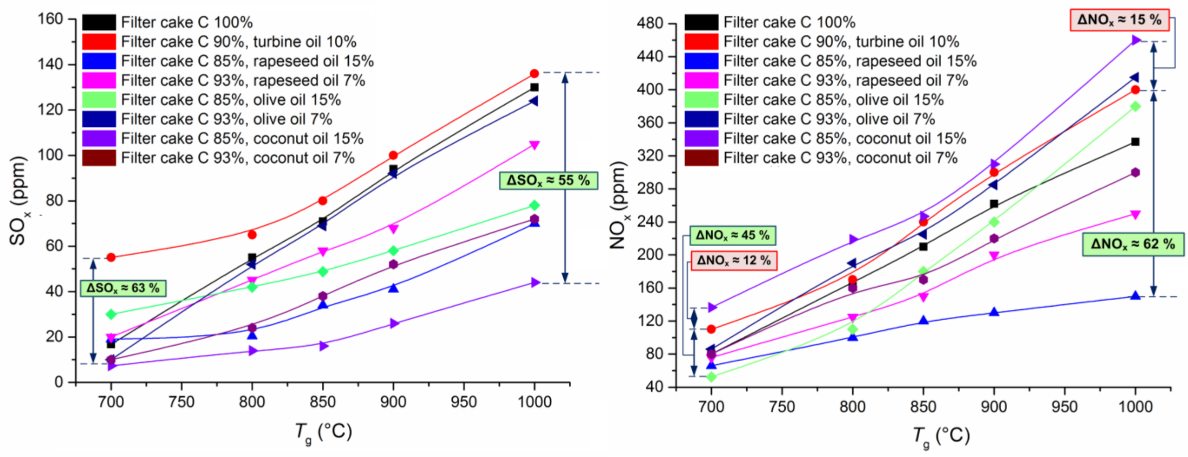
Figure 3. Scheme of experimental setup

For the experiments a fuel sample was weighed using analytical balance with a readability of 0.01 grams. The sample mass in each experiment varied in the range 0.5–1.5 grams. A coordinate mechanism (similar to [9]) was used in the combustion chamber to ensure the automatic insertion and fixation of the modular probe of the gas analyzer with fuel sample. The vertical flap with a layer of high-temperature insulation mounted on the coordinate mechanism closed the hole, which serves for the insertion of fuel sample into the combustion chamber. Thus, the excess air ratio α (equal to 1) was controlled. Gaseous products released during heating, ignition and combustion of fuel in the muffle furnace were registered by the gas analyzer. Measurement channels: O_2 (measuring range 0–25 %, permissible error 0.2%), CO (measuring range 0–10,000 ppm, permissible error 5%), CO_2 (derived from O_2) (measuring range 0–CO_{2max}, permissible error 0.2 %), NO_x (measuring range 0–4,000 ppm, permissible error 5%), and SO_x (measuring range 0–5,000 ppm, permissible error 10%). The gas analyzer was connected to PC. The *EasyEmission* software provided continuous monitoring of the flue gas components from the fuel combustion. Under identical initial conditions, from 8 to 10 experiments were carried out in the same series of measurements. Then the results of experiments were averaged, and the confidence intervals and the corresponding random errors were determined. Further, the article provides the series-average values of registered emissions.

3. Results and Discussion

3.1. The effect of adding vegetable oils

The presented below are experimental dependences (Fig. 4) of the main anthropogenic emissions (SO_x and NO_x) depending on the temperature in the combustion chamber at varying concentrations and types of vegetable oils in CWF slurries. The formation of SO_x (Fig. 4.*a*) in the combustion of coal fuel is more dependent on the content of organic sulfur compounds in different samples. High sulfur content leads to strong contamination of combustion products with sulfur dioxide SO_x. Analysis of the obtained dependences (Fig. 4.*a*) has shown that SO_x concentrations increase with increasing temperature in the furnace. At high temperatures, the reactivity of fuels increases (fuels ignite faster), and there is a more active oxidation of fuel elements, in particular sulfur. The highest emissions of SO_x are specific for the compositions based on filter cake with no additional impurities (17–130 ppm) and its mixture with turbine oil (55–136 ppm) . Additives in the form of vegetable oils contribute to the reduction of concentrations, due to complete absence of sulfur in their composition.



a *b*

Figure 4. Experimental dependences of SO_x (*a*) and NO_x (*b*) concentrations on muffle furnace temperature at varying concentrations and types of vegetable oils in CWSP.

Fig. 4.*a* shows that with an increase in the percentage of vegetable oil (from 7 to 15%) in CWSP, SO_x volumes decrease. This effect is especially noticeable at high temperatures. The increase the amount of vegetable oil in the suspension leads to a proportionally decreasing share of the filter cake (coal component). The fuel sulfur in the suspension becomes smaller, consequently the SO_x is

formed less. In accordance with the obtained data of Fig. 4 it is possible to predict further trends in reducing sulfur oxide emissions with increasing the share of vegetable oil in CWSP, that will have a positively effect on the environment. The limitation associated with the oil mass content in the CWSP is determined more the economic part of the energy production process. In this case, waste from processing vegetable oil can be used instead of edible oil, and then the number of limitation will be reduced.

The water presence in the slurry also explains the low SO_x concentration. During its decomposition, free hydrogen forms, which together with carbon monoxide form a reducing medium, decreasing the SO_x [35]. In addition, the combustion temperature and the oxidation rate of fuel sulfur to the corresponding oxides decrease. As a result of experiments it has been found that compositions with addition of 15% coconut oil (10–42 ppm) are characterized by the lowest emissions of sulfur oxides.

The dependences of maximum NO_x concentrations on temperature are shown in Fig. 4.*b*. Experiments have shown that the temperature in the combustion chamber significantly affects the dynamics of the NO_x output. Fuel-nitrogen conversion to NO_x increased with increasing temperature. Higher temperatures led to higher combustion rates and higher concentrations of radicals [16]. It is assumed that HCN is the main nitrogen-containing pyrolysis product [16]. HCN+O=NCO+H. Higher temperatures promote the oxidation of NCO to NO following the reaction NCO+O=NO+CO. In addition, higher temperatures reduce the char and CO concentrations in the combustor, decreasing the heterogeneous reduction of NO on the char surface $NO+CO=CO_2+N_2$ [16].

The cetane number is a significant thermal characteristic of fuel flammability. The higher the cetane number is, the shorter the delay is and the more monotonically the fuel mixture burns [37]. Of all the vegetable oils under consideration, the coconut oil has the highest cetane number (Tab. 3) (index of combustion rate), which allows it to ignite faster than other vegetable oils, thereby intensifying the ignition of the entire mixture, increasing the combustion temperature. Since in fuel mixtures the amount of NO_x increases due to the thermal effect caused by the temperature increase, the excess of nitrogen oxide concentrations for CWSP with 15% of coconut oil (136–460 ppm) (in comparison with the filter cake without impurities) is understandable. In addition to the high cetane number of coconut oil, there is more oxygen in the composition (Table 3); its presence allows oxidizing nitrogen in the atmosphere to form additional NO_x.

The presence of 7% of coconut oil in the suspension of CWF or CWSP can be considered optimal, since such a concentration is sufficient to reduce the delay in the fuel ignition and to increase the evaporation rate of liquid fuel components. CWSP combustion occurs at lower temperatures. As a result, the rate of NO_x formation decreases. A similar situation occurs when using olive oil. A high value of cetane number of 45 (Tab. 3) in conjunction with the low flash point of 210 ˚C lead to a decrease in the CWSP ignition time, an increase in heat release in the chamber, and therefore to an increase in the concentration of nitrogen oxides [40].

Rapeseed oil by more than 60% is unsaturated fatty acids (mainly oleic). The oleic acid has 18 carbon atoms in the chain (C18:1) with a double bond between the ninth and tenth carbon atoms. In turn, the average length of the carbon chain leads to a lower flame temperature (since monounsaturated fatty acids are less stable and have less calorific value) and, therefore, to a decrease in the formation of nitrogen oxides [37]. Moreover, the release of high mass of volatile substances can lead to local fuel enrichment in the vicinity of burning particles, which can prevent the transfer of volume oxygen to the particles and, therefore, prevent the formation of NO_x. In accordance with the data of Fig. 4 the compositions with rapeseed oil have the lowest concentrations of nitrogen oxides (86–250 ppm). Rapeseed oil is characterized by the lowest oxygen content (relative to other oils). Therefore, less nitrogen oxides are formed in reactions involving fuel nitrogen and oxygen. Similar to the case of sulfur oxides, the increase in the mass concentration of oil in suspensions contributed to the reduction of NO_x (due to a decrease in the share of the nitrogen-containing component in the fuel).

From the analysis of the obtained dependences, it may be concluded that for all the studied additives in the form of vegetable oils, the emission ranges for SO_x and NO_x are comparable and lie in the same range. Therefore, to determine the feasibility of using vegetable oils for CLF, it is necessary to conduct a comprehensive analysis that takes into account economic, environmental and energy aspects [35, 41].

To do this, one can use the generalized integral index [8, 35], taking into account the above indicators. This coefficient characterizes the generation of energy per cost of fuel suspension and concentration of the main emissions:

$$D_{CLF}^{NOx \cdot SOx} = Q^{a}_{s,\,V\,CLF} / (C_{CLF} \cdot NO_{x\_CLF} \cdot SO_{x\_CLF}). \quad (1)$$

The combustion heats and costs of the components of the CWS and CWSP are shown in Tab. 1–3. The costs of slurries were determined in proportion to the components' concentrations assuming zero water cost, since process and waste water may be used for the preparation of composite liquid fuels. The industrial waste cost was taken as zero. Only the costs of their transportation (as in the case of filter cake waste coal) were taken into account as 0.0058 $/kg. The cost of coking coal dust was taken to be 0.05 $/kg. The cost of waste turbine oil was 0.088 $/kg. The heat of combustion and the cost of CLF were determined proportional to the concentration of the components.

The results of the generalization are shown in Fig. 5. To illustrate the advantages of CLF, the obtained indicator $D_{CLF}^{NOx \cdot Sox}$ was divided by the respective indicator for coal (Fig. 5):

$$D_{relative} = D_{CLF}^{NOx \cdot SOx} / D_{coal}^{NOx \cdot SOx}. \quad (2)$$

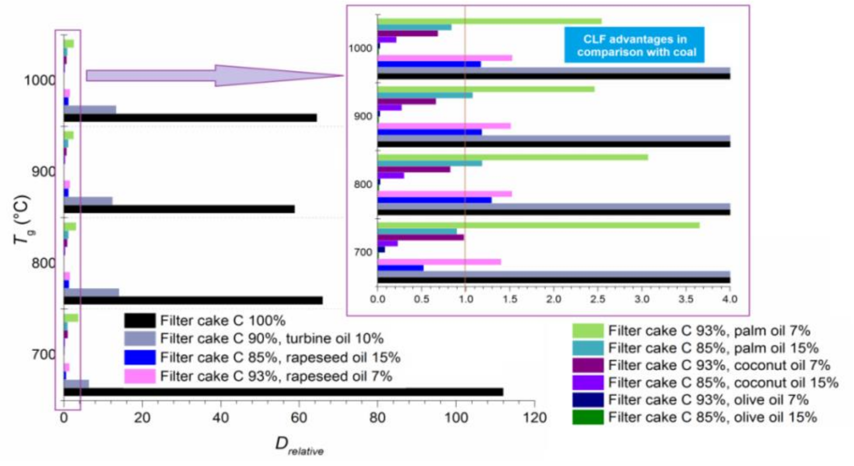


Figure 5. Dependences of relative efficiency indicators of combustion of perspective CLF in comparison with coal at varying temperature in the combustion chamber.

It has been found out that the most promising fuel component is filter cake due to its almost zero cost and low anthropogenic emissions. However, such fuels are much worse in terms of the combustion heat (Tab.1). High indicators, from the point of view of ecology, economy and energy, are specific for the composition based on palm oil (this oil variety has physical and chemical characteristics similar to coconut oil, so the concentrations of anthropogenic emissions were set similarly to coconut oil); so it has a low cost (Tab.3), high production volumes (Fig. 2) and can increase the heat of combustion of CWSP. In view of the high price of olive oil (Tab. 3), using the later as an additive to CWSP is impractical because of the much higher resulting cost of the fuel production process. The addition of rapeseed oil to fuel suspensions also has a positive effect on the energy and environmental performance of CWSP. This fuel component is promising for the countries with vast territories for growing canola and the conditions for the development of the processing industry (for example, Russia, China, and India).

3.2. The use of research results

The work [8] shows significant influence of the liquid combustible components on concentrations of the CWSP combustion products. The introduced integral indicators illustrate the role of the liquid fuel component in the economic and energy aspects of the energy production process, namely that it reduces the ignition temperature and inertia, increases the heat of combustion and the stability of suspensions and is a waste with almost zero cost [8].

The experimental data presented illustrate the great prospects for the use of vegetable oils instead of industrial ones. The energy contribution of vegetable oils is commensurable with the contribution of oil refinery products. High cetane number and calorific value of vegetable oils significantly influence on the burning characteristics of the suspension, reducing the duration of the fuel ignition and increasing the heating effect. However, the environmental benefits of vegetable oils in the CWSP may be more substantial. Now let us calculate the parameters $A^{SOx}{}_{relative}$ and $A^{NOx}{}_{relative}$.

$$A^{SOx}{}_{relative} = SO_{x\_coal} / SO_{x\_CLF}; \quad (3)$$

$$A^{NOx}{}_{relative} = NO_{x\_coal} / NO_{x\_CLF}. \quad (4)$$

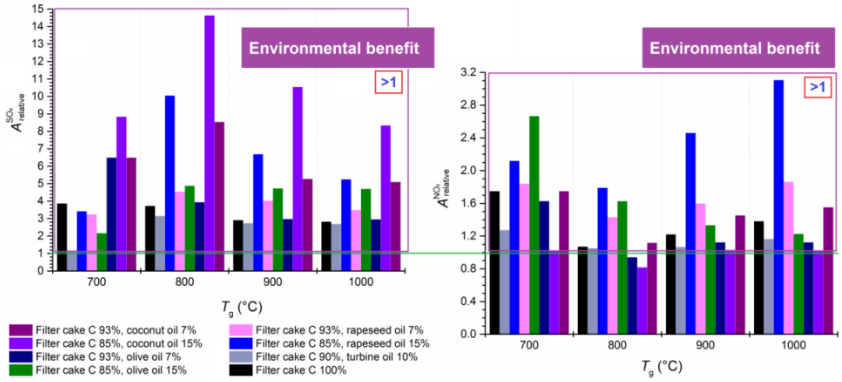


Figure 6. Dependences of relative environmental performance of the combustion efficiency of the CWSP in comparison with coal

It has been established (Fig. 6) that in comparison with coal, the burning of CWSP with admixture of vegetable oil results in 2–15 times less sulphur oxides and in 1.1–3.2 times less nitrogen oxides (depending on oil type, its mass concentration and temperature of burning). The anthropogenic emissions reduction occurs because these oils are biodegradable, non-toxic and can significantly reduce pollution. Vegetable oils and their derivatives lead to a reduction in emissions of oxides of sulphur, nitrogen, carbon monoxide, polyaromatic hydrocarbons, smoke and solid particles. These factors are very important for coal enterprises.

4. Conclusion

(i) The performed experiments have shown that for CLF based on filter cake with admixtures of vegetable oils, the relative combustion efficiency is higher than for CWSP with waste turbine oil. Concentrations of sulfur oxides are lower (compared with CWSP based on turbine oil) by 23–45% at adding of rapeseed oil; by 5–50% at adding of olive oil; and by 50-63% at adding of coconut oil. When using rapeseed oil, nitrogen oxides can be reduced by 5–62%; olive oil – by 5–33%; and coconut oil – by 5–38%. According to the obtained data on sulfur and nitrogen oxides, the most promising additive is rapeseed oil. The concentrations of anthropogenic emissions are lower for compositions with this oil in the temperature range of 850–1000 °C than for a filter cake without additives.

(ii) The calculated complex criterion D_{relative}, taking into account the calorific value, cost and environmental indicators, proves that the fuels with the admixture of vegetable oils considered in this work are inferior to CWS and CWSP based on coal and oil refining waste, mainly, in the cost of components. The detected decrease in anthropogenic emissions cannot numerically compensate for this fact. However, the vegetable base of the fuels is not toxic. Unlike fossil fuels, they are derived from renewable resources. The calculated indicators $A^{SOx}{}_{relative}$ and $A^{NOx}{}_{relative}$ clearly illustrate the ecological prospects of vegetable oils, which are manifested in lesser emissions of SO_x and NO_x: 2–15 times and 1.1–3.2 less, respectively.

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Abbreviation

CLF – coal liquid fuels
CWS – coal-water slurries
CWSP – coal-water slurries containing petrochemicals

Nomenclature

A^d – ash level of dry sample, [%]
$A^{NOx}{}_{relative}$ – relative parameter describing the NO_x, [–]
$A^{SOx}{}_{relative}$ – relative parameter describing the SO_x, [–]
C^{daf} – fraction of carbon in the sample converted to a dry ash-free state, [%]
C_i – cost of components, [$]
$D_{relative}$ – relative complex parameter, [–]
$D_i{}^{NOx\&SOx}$ – relative parameters describing the heat of coal, CWS or CWSP combustion with regard to the cost of components and concentration of emissions NO_x and SO_x, [MJ$–1ppm–2]
H^{daf} – fraction of hydrogen in the sample converted to a dry ash-free state, [%]
N^{daf} – fraction of nitrogen in the sample converted to a dry ash-free state, [%]
NO_x – concentration of nitrogen oxides, [ppm]
O^{daf} – fraction of oxygen in the sample converted to a dry ash-free state, [%]
S_t^d – fraction of sulfur in the sample converted to a dry state, [%]
SO_x – concentration of sulfur oxides, [ppm]
T_f – flash-point of liquid component, [K]
T_g – air temperature, K
T_{ign} – ignition temperature of liquid combustible component, [K]
$Q^a{}_{s,V}$ – heat of combustion, [MJ/kg]
V^{daf} – yield of volatiles to a dry ash-free state
W^a – moisture, [%]

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