Increasing the energy efficiency and environmental safety of the operation of small-volume furnaces by adding a water-fuel mixture and organic components

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Abstract. Industrialisation is trending manufacturing revolution vector, an urgent task is to increase the energy efficiency and environmental safety of small-volume furnaces processes, which are widely applied in the agricultural industry, asphalt concrete plants, etc. In many countries, there are practically no working coal mines or open-pit mines left. However, in a number of regions, coal waste remained in the form of coal dust, ash or in the form of sludge. Utilization of coal dust by preparation of coal-water fuel (CWF) with subsequent combustion of the mixture is currently being applied as the most suitable method. The article discusses improvement of the technology for the preparation of coal-water fuel by applying the effects of hydrodynamic cavitation and adding waste from the livestock complex.

1 Introduction

Successful adoption fuels based on coal-water slurry (CCS) into the industry provides for preliminary work on finding the optimal conditions for obtaining CCS, working out the compositions and selecting the appropriate additives so that the resulting fuels have the physicochemical properties necessary for technological application. The standard technological scheme for the production of CWF provides for the putting in of coal and industrial water; impurities in the form of additives and oil production wastes are also not excluded.

The advantages of using the CWF technology include the require reducing emissions at enterprises in settlements and the coastal zone and decreasing in the cost of heat and electricity due to the low cost of CWF.

The efficiency of combustion of water-coal fuel in boiler furnaces is confirmed by the examples of experimental combustion in Russia and in other countries. In China, Japan, Sweden, the USA and etc. there are operating plants for the preparation of coal-water fuel. Beijing Coal Institute together with the company China coal technology and Engineering Group Clean Energy Co., Ltd, and specialized companies have already developed several generations of CWF preparation technology. The introduction of coal-water fuel technology

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makes it possible to involve tens of millions of tons of coal sludge in the country's energy supply, which can serve as one of the components of coal-water suspensions.

In Russia, coal-fired power plants generate about 17% of the total electricity. This figure rises to 45% in Siberia, due to the close location to the main coal production sites. The share of coal generation in heat production in Siberia is 95% [1]. The use of VUS as a liquid energy fuel in Russia is most expedient, in particular, for solving the problem of storing waste from thermal power plants, as well as in order to reduce the load on the atmospheric air.

Despite the fact that coal-water fuel has existed for more than 50 years, the search for the optimal fuel composition continues. The use of plasticizers (surfactants) in the process of obtaining CWF increases the energy properties of low-quality coals with low calorific value, which is proven in studies [2, 3]. While replacing coal with water-coal fuel, it is possible to reduce emissions into the atmosphere, in particular, particulate matter by 2.5 times, nitrogen oxides by 2 times, and sulfur oxides by 2.5 times. This is due to the fact that the combustion efficiency of such fuel is about 95%. During the combustion of CWF, a powder remains in the form of white or gray conglomerates, consisting mainly of non-combustible mineral particles, therefore, it simplifies the solution of the complex problem of catching fly ash. According to the results of numerous studies (for example, [4]), it has been established that the co-firing of biomass with coal significantly increases the energy efficiency of CWF and a decrease in SOx and NOx emissions is observed. Composite fuel based on natural resources or organic waste using coal-water suspensions has the main advantages: manufacturability, environmental friendliness, energy efficiency and safety. The article [5] investigated the possibility of recycling waste engine oil in the composition of a coal-water suspension. It was found that the net calorific value of such fuel increases.

The use of composite CWF is a real opportunity to replace not only solid fuel and ineffective methods of its combustion, but also scarce liquid and gaseous fuels [7]. This paper presents the results of studies on the development of a technology for producing CWF based on brown coals of the Kansk-Achinsk coal basin and its subsequent use as a composite fuel in low-power boilers.

2 Methods

The aim of the study was to improve the technology of fuel preparation by applying the effects of hydrodynamic cavitation and adding organic waste from animal husbandry to the coal-water mixture.

2.1 Preparation VEG

During the process of obtaining VEG, coal dust of brown coals of the Irsha-Borodinsky open-pit mine (Kansko-Achinsky coal basin) and water were used. As already noted, such fuel is obtained by mixing crushed coal with water or an aqueous emulsion. The share of coal in the fuel composition can be from 52 to 65%, and the share of the liquid component - from 35 to 48%. It is known that water of any quality can be used for the preparation of CWF, including mine and industrial water; for this purpose, ordinary water without complex additives was used.

The percentage of water varied from 50 % to 60 %. The mixture was processed at a speed of 10,000 rpm.

Table 1. Coal characteristics of the Irsha-Borodinsky open-pit mine.

Group	**2B**
Ash content	6-12 %
Average humidity	35 %
Density	1,5 t/m³
Calorific value	2 800-3 800 kcal / kg
Total sulfur content	0,3-1,0 %
Mass fraction of mineral impurities (rocks)	no more 2 %

It should be noted that the ash is dominated by CaO in concentrations of 25-61 %, the concentrations of toxic and radioactive trace elements are insignificant. Content SiO_2 – 52%, Fe_2O_3 – 6%, Al_2O_3 – 6%, CaO – 25%, MgO – 5%, K_2O – 1%, Na_2O – 1%, SO_3 – 5%.

In the developed technological scheme for the production of CWF, mixing of coal dust with water occurs in a rotary-type supercavitation mixer under the influence of the effects of hydrodynamic cavitation, the main function of which is to homogenize and increase the stability of the coal-water suspension (Fig. 1).

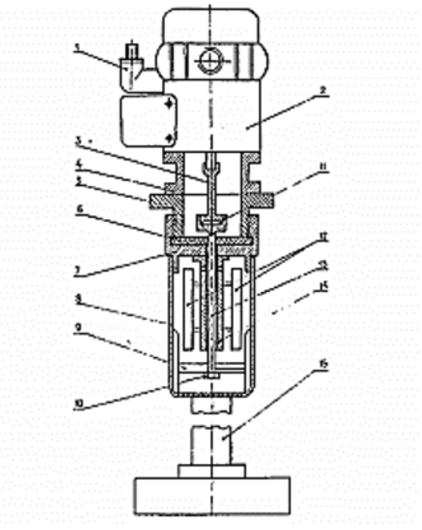

Fig. 1. Supercavitation mixer (emulsifier) diagram:

1 - electrical connector, 2 - electric motor, 3 - intermediate roller, 4 - support ring, 5 - table, 6 - seal, 7 - sleeve, 8 - glass, 9 - cavitator, 10 - nut, 11 - coupling, 12 - hydraulic brake , 13 - cavitator shaft, 14 - bushing, 15 - tripod

The presence of a hydraulic brake 12 allows to maintain an effective homogeneous mode of fluid processing. The design features of the installation include a removable working chamber 8 and a cavitator 9 with a shaft 13, a bushing 14 and a hydraulic brake 12, which allows antiseptic treatment of the parts of the installation in contact with the object of study. A specially designed power supply unit of the electric drive allows smoothly changing the rotor speed in the range of 0–15 • 103 rpm. The design of the laboratory blender is based on the use of a supercavitating impeller 2, which is a wedge-shaped profile with an angle of 30 °, as a working element. The presence of the main hydraulic brake 1 and additional 4 allow preventing the unwinding of the fluid. The separate shaft of the cavitator 3 and the electric motor allows to smooth change the number of revolutions of the rotor and the processing time in wide ranges [9].

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2.2 Studies to determine the material composition

To study the combustion process and determine the material composition of ash, tests were carried out on the combustion of samples of composite fuel and solid coal from the Irsha-Borodinsky open-pit mine. Three samples were accepted for research:

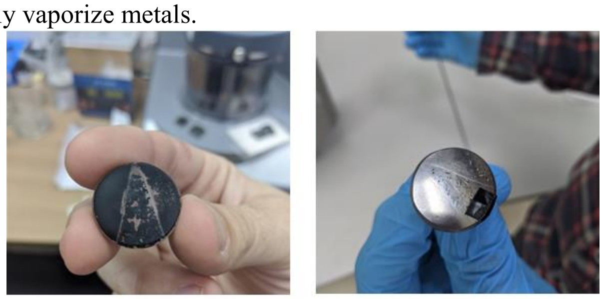
Sample 1. VUS (coal dust - 30 gr., Water - 30 gr.)

Sample 2. Hard coal.

Sample 3. VUS (coal dust 45 gr., Water - 55 gr.).

The chemical composition of the samples was investigated in a polished block, 3 types of burnt fuel were fixed in the block with an epoxy substance, this is a binder mass with neutral characteristics.

A carbon film was deposited in a Q150T Plus turbomolecular pumping spraying unit manufactured by Quorum Technologies Ltd for vacuum deposition. The system was evacuated using a turbomolecular pump and organic residues were removed from the sample using a high current. The installation is designed for sample preparation for electron microscopy, namely for sputtering samples with oxidizing metals and carbon. It also has the ability to thermally vaporize metals.



1 2

Fig. 2. Checker with samples before (1) and after (2) applying a carbon film.

After preparation, the sample was placed into the chamber of a Tescan Vega Compact analytical scanning electron microscope, where elemental analysis of the sample was performed. A powerful entry-level analytical scanning electron microscope (SEM) provides SEM images and real-time elemental analysis in a single window of TESCAN Essence ™ software, which greatly simplifies the acquisition of data on both the surface morphology of the sample and its local composition.

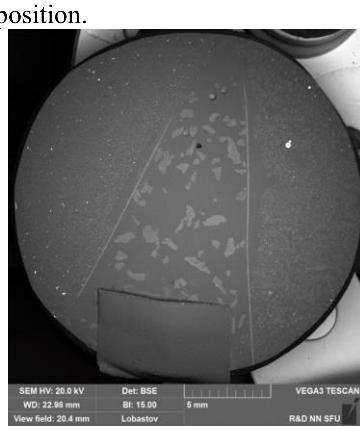


Fig. 3. General view of the samples under a scanning microscope.

One of the most valuable components of fly ash are microspheres (or cenospheres) - a light fraction of fly ash, which is a finely dispersed free-flowing powder consisting of hollow thin-walled spherical particles of aluminosilicate composition, several tens or hundreds of microns in diameter [10].

Aluminosilicate microspheres (AFM) are a hydrophobic, chemically resistant material, in terms of such parameters as hygroscopicity, resistance to acids and alkalis, in terms of water absorption, they are significantly superior to many materials.

Microspheres are formed from the mineral components of coal, aluminosilicates, hydromica, quartz and feldspars, capable of forming eutectic mixtures and a glass phase at a temperature of 1200 °C; therefore, microspheres of various samples are characterized by similar phase and chemical compositions.

The variety of morphological forms of microspheres is explained by the complex transformation process of coal that occurs at various stages (heating, combustion, formation of a viscoplastic state in the hot zone, cooling).

2.3 Preparation of composite CWF with organic waste

To improve environmental friendliness and reduce the cost of fuel, experiments were carried out as a result of which an optimal model of the fuel mixture with the inclusion of organic components was obtained. The mixture was prepared in a supercavitation mixer; organic waste from rabbit farms was added to the previously obtained VES in a ratio of 0.5: 1 to coal dust. The suspension was brought to a homogeneous (uniform) state during stirring for 20 minutes. The CWF obtained with the use of the effects of hydrodynamic cavitation is characterized by high stability and can remain stable for a long time. It is known that organic waste from rabbit farms is a fairly high-calorie waste, therefore the presence of this component in the CWF composition will increase the energy efficiency of the fuel and, as a result, will solve the problem of waste accumulation.

3 Results

X-ray analysis of samples from the surface of microspheres showed that the main elements of the shells of microspheres – это Al, Si, Fe, K, Na, Mg, Ca and O.

Table 2. Elemental analysis results.

Chemical element	Content,% (Sample 1)	Content,% (Sample 2)	Content,% (Sample 3)
O	43.3	**45.7**	39.4
Fe	24.41	**9.8**	35.6
Si	17.5	**18.3**	3.2
Ca	7.1	**13.8**	6.68
Al	4.6	**3**	3.25
K	0.8	**2.29**	0
Mg	0.75	**2.7**	0.26
S	0.5	**0.9**	0.16
Sr	0.3	**0.04**	0.5
Cl	0.2	**0.02**	0.01
Na	0.14	**0.16**	0.02
Ti	0.1	**0**	0.15
P	0.05	**2.3**	0.008
Mn	0	**0**	0.15

Compared to sample 2, samples 1 and 3 (VUS) have a relatively high value of iron compounds. Also, the VES samples contain porous particles consisting of quartz, iron, aluminum and silicon oxides. The formation of these compounds depends on the physical state of the fuel and combustion parameters. According to material analysis, the dark areas in the image are pure carbon..

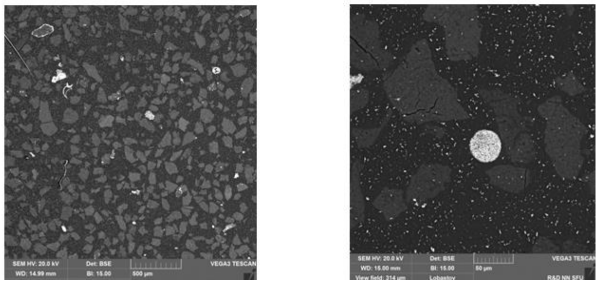


Fig. 4. Sample 1.

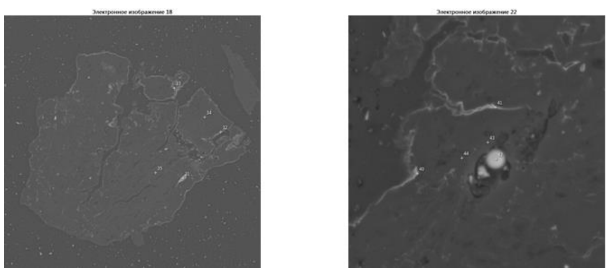


Fig. 5. Sample 2.

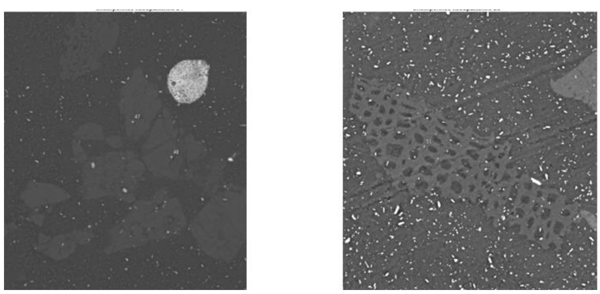


Fig. 5. Sample 3.

In samples 1 and 2, a decrease in the concentration of calcium, magnesium and potassium compounds is observed against the background of sample 3, this is explained by the increased content of cavitated water in the original sample. The main distinguishing feature of coal-water slurry samples is the reduction of sulfur compounds in combustion residues.

It should be noted that a film of calcium phosphate was found in sample 2 (the film was not observed in samples 1 and 3), it can be assumed that during the combustion of solid coal, phosphorus anhedrides were formed and, interacting with calcium, a film was formed.

4 Discussions

On the basis of the experimental data obtained, a scheme of an installation for preparing CWF for combustion was proposed, with the possibility of utilizing waste from livestock enterprises through the use of a two-stage supercavitation process for a mixture of fuel with organic matter when preparing the mass for combustion. At the same time, the combustion parameters of the fuel mixture are improved, in particular, heat losses due to underburning are reduced and, as a consequence, the size of the furnace is reduced.

The technical result of the installation for the preparation of a water-fuel mixture with the inclusion of organic components is achieved using a sequential scheme of devices:

- supercavitation reactor, as an element of the first stage of fuel preparation, into which water and coal are supplied, and the coal is crushed in the device;
- mixer in which animal waste is added;
- supercavitation homogenizer, as an element of the second stage of fuel preparation, to increase the homogeneity of the fuel mixture composition in order to improve combustion parameters;
- pump for transporting the prepared fuel mixture using a stream of water;
-heat generator, the furnace of which is equipped with nozzles for atomizing fuel.

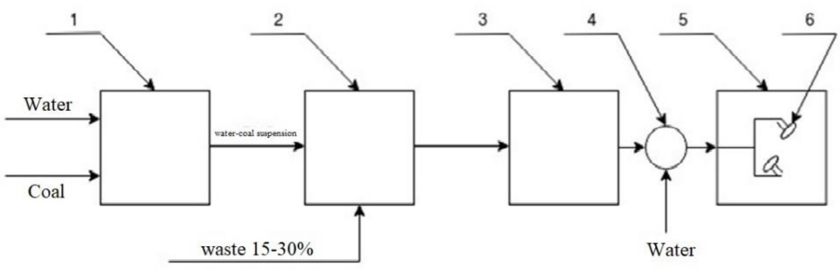


Fig. 6. Schematic diagram of an installation for preparation for combustion of a water-fuel mixture with organic components.
1 - supercavitation reactor; 2 - mixer; 3 - supercavitation homogenizer; 4 - pump; 5 - heat-using device - boiler, 6 - nozzles

A positive effect when using two-stage cavitation is the heating of the fuel mixture during fuel processing for combustion, which makes it unnecessary to preheat the fuel before feeding it to the nozzles of the furnace. The installation function is performed in two stages.

The first stage of fuel preparation. The flow of water and coal preliminarily crushed to a diameter of 10-30 mm is sent to a supercavitation reactor, where, due to the rotation of the blades, coal is crushed and a coal-water suspension is formed and enters the mixer, into which animal waste is added in the amount of 15-30% of the volume of the previously obtained mixture. After the mixer, the fuel goes through the second stage of processing.

Second stage of fuel preparation. The flow of the fuel mixture undergoes additional processing in a supercavitation homogenizer, in which, due to the rotor blades, the homogeneity of the composition is increased to the state of a homogenized mixture, microexplosions are formed due to the pressure difference, as a result of which the temperature of the mixture rises. As a result, there is no need to preheat the fuel mixture before combustion, which simplifies the design of the heat generator and contributes to the achievement of optimal combustion parameters.

From the supercavitation homogenizer, the fuel mixture is pumped into the furnace of the heat generator by means of a stream of water. In the furnace, the flow is sprayed using nozzles located in the horizontal plane at an angle of 10-45 ° relative to each other, since such an arrangement increases turbulization and lengthens the trajectory of fuel particles.

5 Conclusions

The processing of the captured coal dust at TPPs into cavitation water-coal fuel for subsequent combustion in low-power boilers makes it possible to increase the efficiency of fuel preparation and minimize energy consumption for its preparation. The amount of coal dust at TPPs is enormous and amounts to hundreds of tons per day. The use of VUT makes it possible to increase the efficiency of coal combustion, utilize coal sludge, reduce the explosion hazard of fine coal dust, and significantly reduce the amount of emissions into the atmosphere.

The conducted elemental analysis of the samples of the combustion of VEG showed a significant decrease in sulfur compounds in the combustion products.

A certain optimal composition of the composite fuel excludes the use of additives and plasticizers, the finished coal-water suspension remains stable for a long time.

The proposed technology for the preparation of coal-water fuel with the addition of organic components makes it possible to utilize waste from livestock breeding complexes.

The use of the proposed installation scheme for fuel preparation eliminates the need for preheating the mixture due to microexplosions of air bubbles in the process of two-stage cavitation preparation, which contributes to the achievement of optimal combustion parameters. An increase in the completeness of fuel combustion is also ensured due to the location of the injectors in the horizontal plane at an angle of 10-45 ° relative to each other. Such a structure lengthens the trajectory of the fuel particles, reduces underburning and increases the productivity of the process, which makes it possible to reduce the overall dimensions of the furnace.

Economic effect of the introduction of CWF can be achieved by reducing the cost of fuel delivery; application of coal dust as a raw material, which is usually disposed as a waste; due to the achievement of a more complete combustion of coal in the form of CWF relative to layer combustion, which leads to the absence of costs for the utilization of unburned coal.

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