OPTIMIZATION OF PRODUCTION AND IMPROVEMENT OF CHARACTERISTICS OF WATER-COAL FUEL SUSPENSIONS BASED ON HIGH-ASH COALS

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ABSTRACT

This article explores the possibilities for improving the characteristics of water-coal fuel suspensions (WCFS) based on high-ash coals from Uzbekistan. Investigations indicate that the incorporation of stabilizing and plasticizing additives, such as sodium and calcium hydroxides, can result in notable enhancements in both rheological characteristics and calorific value of WCFS. These results are important for optimizing production and increasing the technological suitability of WCFS based on high-ash coals from Uzbekistan, which allows them to be used as highly effective fuels. This investigation is a significant advancement towards the progress and enhancement of fuel blends and can be valuable for engineers and manufacturers who are engaged in the manufacturing process of WCFS.

Keywords: coal, water-coal fuel suspensions (WCFS), high-ash coals, sodium and calcium hydroxides, rheological characteristics, heating value, viscosity, ash content, dynamic shear stress.

INTRODUCTION

The depletion and increased cost of oil and gas reserves have heightened the importance of solid fuel in maintaining the fuel and energy balance. However, the use of carbon-based fuels such as coal poses significant environmental challenges, necessitating the development and implementation of new eco-friendly coal technologies. One such promising technology is water-coal fuel suspensions (WCFS), which offer economic, environmental, and operational benefits compared to traditional burning methods [1, 2]. WCFS promotes efficient coal combustion, utilization of coal slurry, reduced risk of explosions from fine coal dust emissions, and decreased emission of nitrogen and sulfur oxides into the atmosphere. Furthermore, the use of relatively inexpensive fuels like WCFS contributes to energy and material resource savings while limiting environmental pollution.

WCFS is not a mechanical mixture of coal and water but rather an artificial composite fuel that forms a single fuel entity [3, 4]. It functions as a colloidal dispersed fuel system with no bulky components, thanks to the high surface tension of the dispersing medium and electrostatic tension at the solid/liquid phase interface [5 - 7]. This prevents separation during spraying even at high energies, allowing each droplet of WCFS to maintain its original composition and characteristics. The presence of all fuel components throughout the droplet, facilitated by the solid phase of WCFS as its colloidal component, enables their active participation in chemical reactions at all stages of combustion. The consistency in composition and fuel properties ensures the stability of equipment operations where WCFS is utilized.

The development of technology to produce WCFS has received significant attention recently [8]. Researchers have highlighted the importance of anthracite and bituminous coals in this process. Several countries, including Japan, China, Italy, the United States, Russia, Ukraine, and Canada, are actively exploring and promoting this technology. It is estimated that the global market for coal-water slurries was worth USD 2398 million in 2021, with an expected annual growth rate of 15 % to reach USD 6366 million by 2028 [9].

One example is Japan COM Co. Ltd, a joint Japanese Chinese enterprise engaged in large-scale production of water-coal fuel (WCF) for supply to Joban Joint Thermal Power Station in Nakoso, Japan [10, 11]. China has been researching WCFS since the early 1980s and has rapidly adopted Russian technologies [12]. China is currently the leader in WCFS applications due to its heavy reliance on coal as the primary energy source. To address environmental concerns, the Chinese government established the National Center for WCFS of the Coal Industry. The country aims to increase WCFS production to 100 million tons per annum within the next twenty years [10].

In the United States, a coal utilization program has been implemented since the 1990s, with significant funding allocated towards the creation, transportation, and use of WCF [8, 9]. Belarusian and Ukrainian scientists have also conducted research on WCF production and usage in industry, although efforts to construct WCF preparation factories are still in their early stages [13, 14]. A pilot project for WCF production has been tested in Ukraine, and implementation of this technology could lead to significant natural gas savings.

Research and utilization of WCF remain relevant globally. Ongoing improvement and innovation efforts are being carried out in Japan, Italy, the United States, Canada, and other countries. The rheological characteristics, stability, and thermal efficiency during combustion of highly concentrated water-coal suspensions are important factors to consider. The fluidity properties of these suspensions are influenced by coal properties, additives, and water composition. The size and volume of pores in coal can affect viscosity and fluid behaviour. The mineral matter of coals also plays a significant role in the properties of highly concentrated water-coal suspensions [15].

Grinding of coal is an important aspect in the preparation of highly concentrated WCS as it allows control over particle size distribution [16 - 18]. Studies have shown that improving the characteristics of highly concentrated WCFS can be achieved by using a certain amount of fine fraction of solid material [19 - 22]. Uzbekistan has significant coal reserves, including brown coal and hard coal, and there is potential to utilize these deposits for the creation of solid fuel tablets.

EXPERIMENTAL

Methods for studying composition and structure

In the open-pit mines of the brown coal basin in Uzbekistan, grade-quality coals of brands: B1 (2BPK), B2 (2BOMSSH-B1), B3 (2BOMSSH-B2), B4 (1SSKOM) are mined.

The studied samples of coal were provided by the state-owned company "Uzbekugol".

To determine the composition and structure of the initial coal, comprehensive physicochemical analyses were carried out. The first of these was X-ray diffraction analysis using an Empyrean PANanalytical XRD diffractometer. The minimum scanning step of this setup is 0.0001° with an angle reproducibility of < 0.0002°.

The elemental composition and quantitative content of elements in the samples were determined using energy-dispersive X-ray fluorescence spectrometry. Scanning electron microscopy with EVO MA10 SEM was used to determine surface morphology and element composition as well.

IR spectra were taken on a Nicolet iS50 Thermo Fisher Scientific Avatar 360 FT-IR spectrometer with Fourier transformation in the frequency range of 400 - 4000 cm^{-1}. Thermogravimetric and differential thermal analyses were carried out on a Q - 1500 D derivatograph in the temperature range of 20 - 1000°C in an air atmosphere at a heating rate of 5° min^{-1}.

The physics-chemical characteristics of coal were determined in accordance with the requirements of state standards such as GOST R 56357 - 2015, GOST 8302 - 87, GOST 8298 - 89, and TSh12 - 18:2001. The contents of carbon and ash in the samples were determined by absolute combustion of the material in a tubular furnace using an accelerated method according to GOST 2408.1 - 95.

To obtain a coal-water suspension, coal was ground in a single stage using a laboratory ball drum mill of type VEB Metallverarbeitung 4600 Wittenberg BT. The mill had a productivity of 2 kg h^{-1}. Prior to feeding into the mill, the coal underwent crushing to a particle size not larger than 3 mm. In the preparation of a coal slurry based on brown and hard coals, coal grinding down to a particle size of 50 microns was necessary while maintaining a certain proportion. The quantities of coal and water were calculated based on the dry mass of coal so that the solid-phase content in the suspension corresponded to the specified value. The milling time in the mill was empirically determined based on the yield of particles less than 0.05 mm. The quality of the coal-water suspension, including its suitability as boiler fuel, viscosity, and resistance to separation, was determined by the content of fine fractions (less than 50 μm). Finer grinding led to a significant increase in the viscosity of the suspension and energy consumption during preparation. Coal was preferably ground to a size less than 50 microns to ensure effective combustion of dusty brown and hard coal in heat generators. The obtained suspensions were homogenized by mixing with a mixer in specially prepared cylindrical vessels every 5 - 15 min at a rotation speed of 800 revolutions per minute for one hour.

The measurement of the rheological characteristics of jet engine fuels was conducted using a Brookfield RVDV-II+Pro rotational viscometer. The particle size distribution of the milled samples was determined using a sieve method. Various stabilizing and plasticizing additives including NaOH, $Ca(OH)_2$, and surfactant - polymer MPC - 1 were used to regulate the rheological properties of the fuel. It should be noted that stabilizing additives such as NaOH and $Ca(OH)_2$ were employed to create sedimentation stability (stability) of the obtained jet fuels, while plasticizing additive surfactant (0.05 % aqueous solution of MPC - 1), accounting for 1.0 % of the total fuel mass, was utilized to enhance their flowability. Water-soluble polymer MPC - 1 with a main substance content of not less than 17 - 18 % is developed and produced by LLC "MAN'ON ZIYO, Uzbekistan." The MPC - 1 is derived via alkali hydrolysis from waste production of polyacrylonitrile (PAN) fiber - nitron TSh 6.1 - 66 - 98 AO "Navoi azot", Uzbekistan.

RESULTS AND DISCUSSION

Characteristics of the investigated coals.

The qualitative characteristics of the coals are presented in Table 1.

Based on research conducted to identify the composition and characteristics of coal samples in accordance with the requirements for coal quality suitable for producing activated carbon, coal samples with a volatile dry ash-free yield of 39 - 44 % and an ash content of 12 - 15 % can mainly be used. The most suitable coal in this regard is the Angren brown coal of the B1 grade and the Shargun stone coal of the B4 grade. In addition, conditioned commercial Angren brown coal of the B2 and B3 grades were also investigated, considering the possibility of large-scale application of activated carbon. The physics-chemical characteristics of the selected coal samples are presented in Table 2. From the data in the table, it can be seen that the selected samples of B1 and B4 coal grades are characterized by low ash content (10.0 and 10.5 %) and low sum of carboxylate and hydroxyl groups in the coal fuel (1.72 and 0.56 mg-eq g^{-1}) compared to the higher ash content conditioned commercial coal of the B2 and B3 grades, where their ash content values are 34.7 and 50.7 %, respectively, and their sum of carboxylate and hydroxyl groups content are 1.56 and 1.66 mg-eq g^{-1}, respectively.

The volatile matter yield for B1 and B4 coal grades is 34.2 % and 35.4 %, respectively, whereas for high-ash coals, such as B2 and B3, it is 36.6 % and 40.8 %, respectively. The lower heating value for low-ash coals, such as B1 and B4, is 3600 and 6200 kcal kg^{-1}, respectively, while for high-ash coals, such as B2 and B3, it is 2700 and 2300 kcal kg^{-1}, respectively. The

Table 1. Qualitative characteristic of coals.

Grade (group)	Particle size, mm	Ash content, %	Moisture content, %	Lower heating value, kcal kg^{-1}
B1	50 - 200	14.8	36.0	3600
B2	≤ 50	34.3	41.0	2700
B3	≤ 50	39.4	40.3	2300
B4	13 - 100	25.0	13.4	6200

higher heating value for these coal grades, namely B1, B4, B2 and B3, is 8160, 8720, 7040 and 6290 kcal kg^{-1}, respectively. The lower heating value is calculated based on the maximum moisture content since the working moisture values for some samples are underestimated due to coal drying during grinding and storage. The coal samples tested varied widely in terms of their maximum moisture content, ranging from 10.0 % to 16.7 % (Table 2). The high-ash coal B3 had the highest moisture content of 16.7 %, indicating a significant number of clayey impurities.

Chemical-mineralogical and dispersion composition, physical and technological properties of coals

As the chemical composition of the inorganic part of coals plays a significant role in the formation of the suspension structure, the chemical analysis of the original coals and their elemental analysis of the ash components were carried out. The content of mineral components in coals varies widely - from units to tens of percent or more. The main mineral impurities in brown and black coals are clay minerals, iron sulfides, carbonates, and quartz. The peculiarities of the chemical composition of ash affect the fluidity and stability of water-coal fuels.

Table 3 presents the chemical composition of coal ashes from Uzbekistan.

Analysis of Tables 3 and 4 reveals that at an Angren brown coal ash level of 12.8 % the silica oxide content was less than 45.66 %. With further increase in ash content in the range of 34.7 - 50.7 %, the silica oxide content increased to values between 56.97 % and 59.88 %, while the CaO content ranged from 14.62 % - 14.95 %. At Shargun coal ash levels of 10.5 %, the silica oxide content was less than 28.84 % (CaO content being 16.56 %). Both types of coal, both Angren brown and Shargun, contain silicon in the form of quartz in heavy fractions.

The mineralogical composition of the ash components was determined through X-ray analysis. Mineral inclusions in coal were found to consist mainly of clay minerals, such as kaolinite, present in the form of yellowish-white speckles forming thin lamellar aggregates and grains; sulfides represented by pyrite and marcasite (FeS_2); and carbonates consisting of siderite ($FeCO_3$) and occasionally calcite ($CaCO_3$).

Table 4 presents the results of a study on the effect of grinding time on the particle size distribution of coal. The analysis of the table data suggests that an increase in grinding time leads to an increase in the yield of coal particles measuring less than 0.05 mm. This, in turn, promotes the stability of the suspension.

It is noteworthy that obtaining a water-coal fuel suspension (WCFS) with optimal technical characteristics is a pressing problem in the field of power engineering and energy processes. Coal dispersion, including the optimal fractional component, plays an important role in ensuring efficient combustion and suspension stability. Therefore, studying the impact of

Table 2. Characteristics of the investigated coal samples.

Sample	Yield of volatile matter, %	Fuel mass content, mg-eq g^{-1}		Higher heating value, kcal kg^{-1}
		COOH	OH	
B1	34.2	0.31	1.51	8113
B2	36.6	0.22	1.59	7112
B3	40.8	0.17	1.56	6213
B4	35.4	0.34	0.24	8519

Table 3. Chemical composition of coal ashes.

Sample	Content, % on an air-dry basis											
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MgO	MnO	CaO	Na_2O	K_2O	P_2O_5	SO_3	ppp
B1	45.66	0.48	14.78	4.67	2.62	0.18	13.64	0.67	0.75	0.12	11.35	3.02
B2	56.97	0.69	21.61	4.84	1.01	0.05	14.62	0.37	1.35	0.14	3.50	3.10
B3	59.88	0.81	21.78	4.94	0.91	0.03	14.95	0.18	1.58	0.12	2.24	3.12
B4	28.84	0.17	9.55	20.25	1.81	0.36	16.56	0.18	0.19	1.10	18.36	< 0.1

Table 4. Fractional composition of crushed coals.

Grinding duration, min.	Fractional composition in mm, %			
	≤ 0.05	0.05 < 0.1	0.1 < 0.16	≥ 0.16
B1				
20	21	24	28	27
40	27	33	24	16
60	31	40	19	10
240	78	22	0	0
B2				
60	26	16	10	48
120	30	15	15	40
240	34	32	17	17
360	49	29	12	10
480	78	17	3	2
B3				
60	22	14	12	52
120	26	18	15	41
240	31	29	19	21
360	43	23	16	18
480	66	23	7	4
600	80	11	5	4
B4				
20	11	21	26	42
40	14	28	22	36
60	22	32	18	28
240	52	28	15	5
360	82	18	0	0

grinding parameters, such as duration, on the formation of coal particle size distribution in WCFS is important for optimizing the production and use of this type of fuel.

The research findings show that achieving coal fraction content below 50 microns at 78 - 80 % level in WCFS based on brown coal requires a grinding time of 240 min, whereas grinding time of 360 min is necessary for hard coal. These results highlight the importance of optimizing grinding time depending on the coal type to achieve the desired dispersion and quality of the resulting suspension.

The influence of temperature on structural viscosity and dynamic shear stress of fuel suspensions

Rheological characteristics of fuel suspensions are the key indicators that determine their technological suitability, as they are determined by physics-chemical processes between the solid and liquid phases of a system and therefore must be considered in relation to specific usage conditions. The rheological characteristics of fuel suspensions were studied within a temperature range of 20 - 60°C, which was chosen based on possible operational parameters of the suspension. The solid phase contents ranged from 36 - 55 %. To determine the rheological characteristics at different temperatures, suspension samples were placed in the measuring chamber of a viscometer and thermostated for 15 minutes with the measuring system. Fig. 1 and 2 show the dependencies of structural viscosity and dynamic shear stress of fuel suspensions on temperature. It was found that with increasing temperature from 20 - 60°C, both the structural viscosity with and without plasticizer additives decreased by almost 1.5 - 2 times. The use of plasticizers significantly reduced the structural viscosity of the suspensions, allowing for an increase in the amount of solid phase. Moreover, the dynamic shear

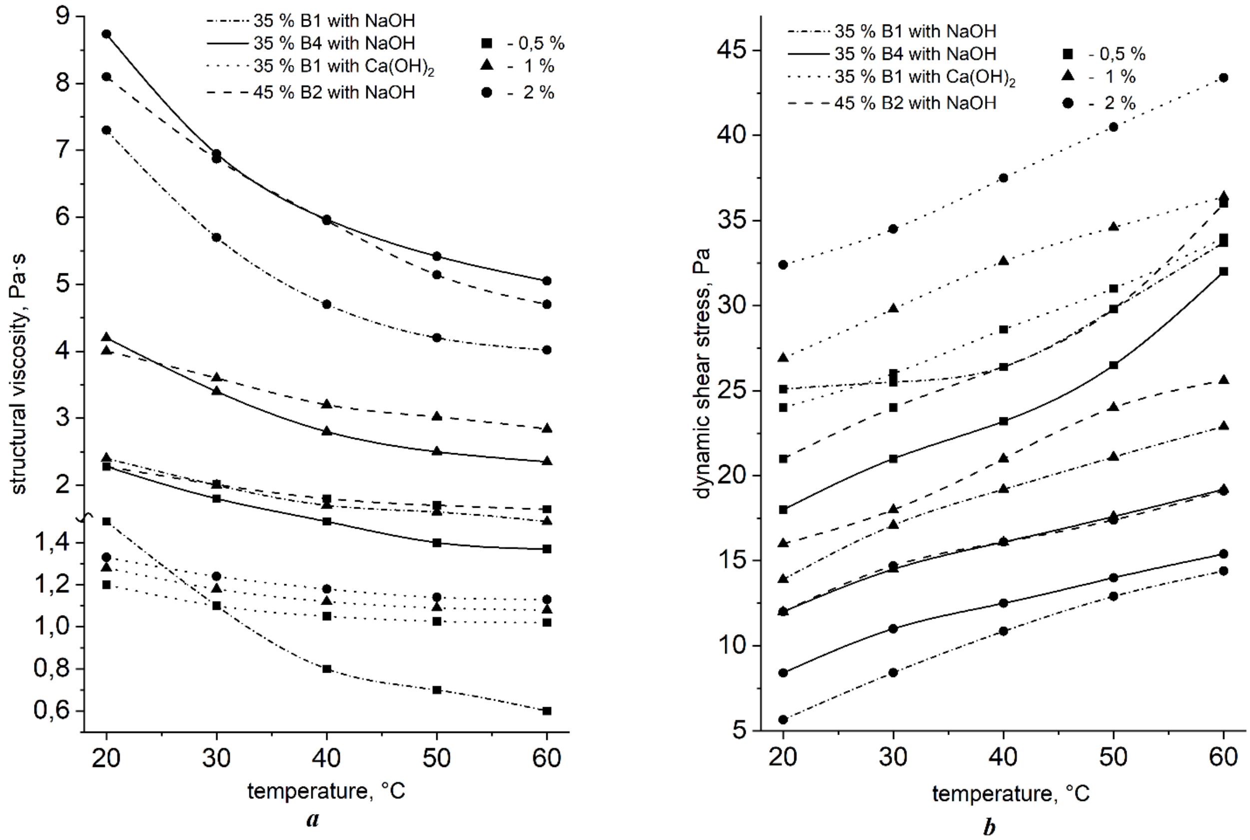

Fig. 1. Dependence of structural viscosity (a) and dynamic shear stress (b) on temperature for WCFS obtained from B1, B2, and B4 coals. The content of additives (NaOH, $Ca(OH)_2$): 0.5, 1.0, and 2.0 %.

stress of the suspensions increased by approximately 2 times when temperature was raised to 60°C.

Fig. 1 and 2 demonstrate that increasing the temperature from 20 to 60°C in WCFS with NaOH or $Ca(OH)_2$ additives reduces the magnitude of structural viscosity by approximately 1.5 - 2 times, thereby increasing the amount of solid phase present in the suspensions. Using NaOH as a stabilizer results in monotonic increases in dynamic shear stress. For example, adding 2.0 % NaOH increases the value of dynamic shear stress from 9.0 Pa at 20°C to 16.0 Pa at 60°C. Viscosity serves as an indicator for the elastic properties of suspensions and depends on the interactions between solid particles in liquid phase. Similarly, dynamic shear stress in fuel suspensions with $Ca(OH)_2$ also increases with rising temperatures, whereby adding 2.0 % $Ca(OH)_2$ increases its value from 8.5 Pa at 20°C to 14.5 Pa at 60°C. The influence of storage duration and

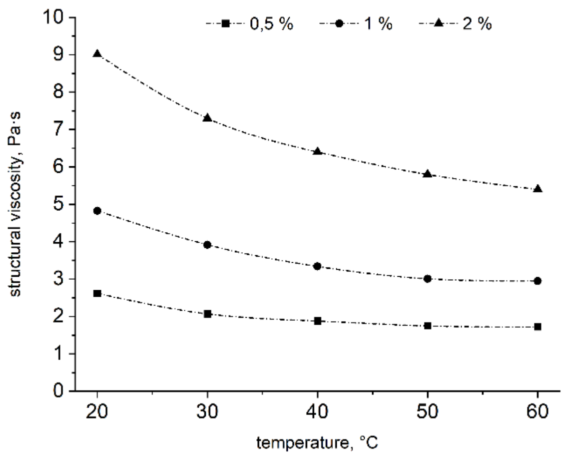

Fig. 2. The dependence of structural viscosity on the temperature of WCFS based on B3 (50 %) with the content of $Ca(OH)_2$: 0.5, 1.0, and 2.0 %.

Table 5. The effect of grinding duration on the degree of comminution and properties of WCFS.

Grinding duration, min	Residue on sieve, %.		Rheological characteristics		
	R_{50}	R_{200}	μ_{str}, Pa s	τ_0, Pa	Stability, h
B1 (not more than 40 % in WCFS)					
10	45	3.5	1.81	29.3	26
20	31	1.5	1.88	28.5	49
30	19	≤ 1	2.01	24.2	118
40	16	≤ 0.7	2.61	14.8	471
50	13	≤ 0.3	2.61	14.4	503
60	9	0.09	2.62	14.3	839
B2 (not more than 45 % in WCFS)					
10	47	3.6	1.86	29.1	23
20	33	2.5	1.92	26.3	45
30	23	1.7	1.99	25.9	98
40	19	≤ 0.8	2.07	23.9	416
50	15	≤ 0.5	2.13	20.8	488
60	11	≤ 0.2	2.31	18.0	798
B3 (not more than 50 % in WCFS)					
10	53	4.6	1.86	28.8	24
20	37	2.8	1.90	26.4	44
30	25	1.5	1.94	24.9	69
40	23	≤ 1.0	2.01	23.3	356
50	19	≤ 0.5	2.12	22.5	450
60	16	≤ 0.3	2.13	21.9	698
B4 (not more than 50 % in WCFS)					
10	46	3.5	1.76	36	24
20	34	2.2	1.80	34	45
30	21	1.3	1.83	32	92
40	18	≤ 0.75	1.85	27	411
50	12	≤ 0.4	1.88	28	598
60	10	≤ 0.1	1.89	26	801

conditions on rheological characteristics of WCFS was investigated. Rheological properties were determined for fuel suspension samples stored over a certain period (up to 40 days). Dynamic shear stress, which characterizes the elastic properties of suspensions and depends on the interaction between solid particles in liquid phase, decreases with rising temperatures from 20 to 60°C due to diminishing particle-particle interactions. Based on this data, it can be concluded that increasing temperature and using specific additives (NaOH or $Ca(OH)_2$) can affect rheological characteristics of WCFS such as viscosity and dynamic shear stress.

Dispersion as the main indicator of stability in WCFS

Table 5 presents the results of a study on the effect of grinding duration on the degree of pulverization and rheological properties of WCFS.

From Table 5, with an increase in grinding duration, the output of coal particle fractions with sizes less than 50 μm (R50) increases, leading to an increase in structural viscosity and stability of WCFS. It is established that to obtain WCFS with 80 % fraction content of coal particle sizes less than 50 μm (R50), grinding for 50-60 minutes using a MBM ball mill type is sufficient.

The rheological characteristics of WCFS, particularly their structural viscosity, are one of the main indicators determining their technological suitability in practice. Therefore, to obtain stable, consistent, and easily flowing WCFS, the values of their structural viscosity were determined both without stabilizing and plasticizing additives, and with the addition of these additives into the composition of fuel suspensions, the results of which are presented in Fig. 3, as well as in Tables 6 - 9.

It was found that with an increase in the solid-phase content in WCFS up to a certain percentage of coal, the values of structural viscosity remain almost constant. However, beyond a certain value of solid-phase content, there is a gradual increase in the magnitude of WCFS' structural viscosity: for B1, B2 and B3 - 38.2 %, 44.1 %, and 46.8 %, respectively, and for B4- 51.0 %.

Increasing the content of NaOH up to 1.0 % or $Ca(OH)_2$ up to 0.75 % leads to sedimentation of suspensions and formation of a hard precipitate. The aqueous alkali, reacting with brown coal, initially converts humic acids into sodium salts in the aqueous phase. Sodium salts of humic acids in an aqueous solution exist as true solutions, and it is precisely this composition that forms the aqueous phase of WCFS at high alkali concentrations (over 2.0 %), ensuring complete conversion of humic acids into their corresponding salts.

At low alkali concentrations, the coagulation process of humic acids occurs, transforming the solution of sodium salts of humic acids into a gel-colloid, which stabilizes the suspension of water and coal and reduces its viscosity. From the conducted research on obtaining WCFS, the maximum allowable amounts of stabilizing

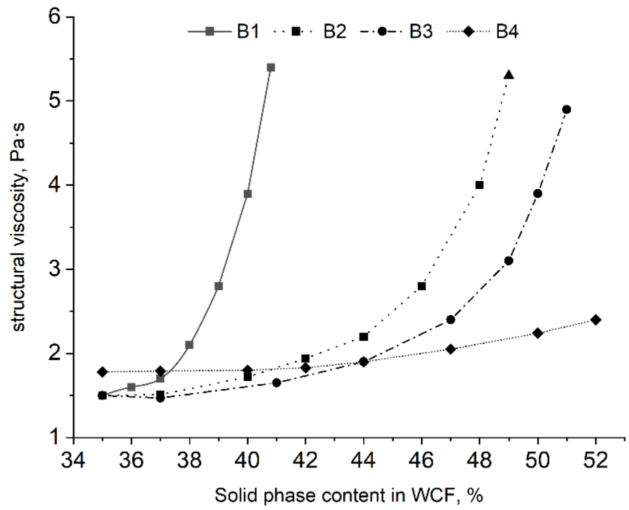

Fig. 3. Dependence of the structural viscosity of WCFS based on B1, B2, B3, and B4.

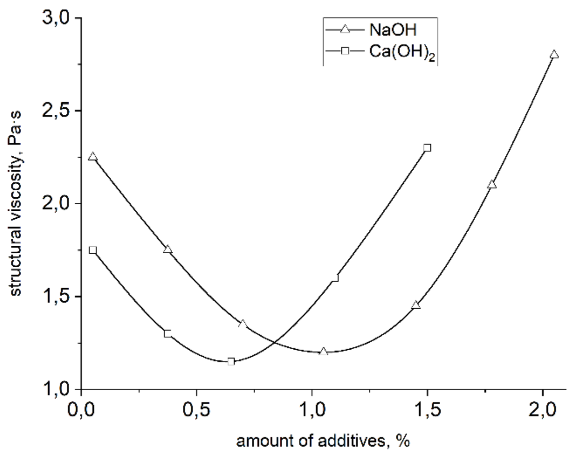

Fig. 4. The dependence of the structural viscosity of WCFS based on B1 on the amount of introduced NaOH and $Ca(OH)_2$.

Table 6. The dependence of structural viscosity and dynamic shear stress of of WCFS based on B2 (42 %) with introduced sodium and calcium hydroxides.

Additive	Amount of additive, %	Rheological characteristics	
		μ_{str}, Pa s	$\tau_{0,}$ Pa
Without additive	-	2.24	21,1
NaOH	1.0	1.16	47.2
$Ca(OH)_2$	0.75	1.17	46.8

Table 7. Dependence of structural viscosity and dynamic shear stress of WCFS based on B1 (45 %) on the amount of introduced sodium and calcium hydroxides.

Chemical additive	Amount of additive, %	Rheological characteristics	
		μ_{str}, Pa s	$\tau_{0,}$ Pa
Without additive	-	2.18	22,3
NaOH	1.0	1.11	51.8
$Ca(OH)_2$	0.75	1.19	43.9

Table 8. Influence of stabilizing and plasticizing additives on rheological indicators and calorific capacity of WCFS based on B1.

Solid phase content, %	Chemical additive	Amount of additive, %	Rheological characteristics		Calorific value, kcal kg^{-1}
			μ_{str}, Pa s	$\tau_{0,}$ Pa	
36	Without additive	-	2.52	15	1918
40	NaOH + surfactant	1.0	2.46	18	2203
38	$Ca(OH)_2$+surfactant	0.75	2.56	14	2012

Table 9. Influence of stabilizing and plasticizing additives on rheological indicators and calorific capacity of WCFS based on B2.

Solid phase content, %	Chemical additive	Amount of additive, %	Rheological characteristics		Calorific value, kcal kg^{-1}
			μ_{str}, Pa s	$\tau_{0,}$ Pa	
42	Without additive	-	2.22	20.3	1823
46	NaOH + surfactant	1.0	2.15	21.8	1998
44	$Ca(OH)_2$+surfactant	0.75	2.38	19.1	1911

Table 10. Influence of stabilizing and plasticizing additives on rheological indicators and calorific capacity of WCFS based on B3.

Solid phase content, %	Chemical additive	Amount of additive, %	Rheological characteristics		Calorific value, kcal kg^{-1}
			μ_{str}, Pa s	τ_{0}, Pa	
45	Without additive	-	2.14	22.5	1618
50	NaOH + surfactant	1.00	2.23	20.8	1829
47	$Ca(OH)_2$+surfactant	0.75	2.11	23.1	1706

Table 11. Influence of stabilizing and plasticizing additives on rheological indicators and calorific capacity of WCFS based on B4.

Solid phase content, %	Chemical additive	Amount of additive, %	Rheological characteristics		Calorific value, kcal kg^{-1}
			μ_{str}, Pa s	τ_{0}, Pa	
50	Without additive	-	1.84	30.6	3336
54	NaOH + surfactant	1.0	1.76	34.8	3611
52	$Ca(OH)_2$+surfactant	0.75	1.96	25.9	3523

additives were established: not more than 1.0 % NaOH and 0.75 % $Ca(OH)_2$ by weight of the total fuel mass.

Tables 9, 10, and 11 present the results of studies related to the influence of stabilizing and plasticizing additives on rheological indicators and calorific value of WCAS based on various types of coal.

Table 9 shows the effect of additives on rheological properties and calorific value of WCAS based on B2. With a solid phase content of 42 %, without any additives, the structural viscosity is 2.22 Pa s, dynamic shear stress is 20.3 Pa, and the heat of combustion is 1823 kcal kg^{-1}. Addition of 1.0 % NaOH + surfactant decreases the structural viscosity to 2.15 Pa s, increases dynamic shear stress to 21.8 Pa, and the heat of combustion to 1998 kcal kg^{-1}. Addition of 0.75 % $Ca(OH)_2$ + surfactant increases the structural viscosity to 2.38 Pa s, reduces dynamic shear stress to 19.1 Pa, and the heat of combustion is 1911 kcal kg^{-1}.

Table 10 examines the effect of additives on rheological parameters and heating value of WCFS based on B3. At a solid phase content of 45 %, without additives, the structural viscosity is 2.14 Pa s, dynamic shear stress is 22.5 Pa, and heat of combustion is 1618 kcal kg^{-1}. Addition of 1.0 % NaOH + surfactant increases structural viscosity to 2.23 Pa s, decreases dynamic shear stress to 20.8 Pa, and increases heat of combustion to 1829 kcal kg^{-1}. Addition of 0.75 % $Ca(OH)_2$ + surfactant decreases structural viscosity to 2.11 Pa s, increases dynamic shear stress to 23.1 Pa, and increases heat of combustion to 1706 kcal kg^{-1}.

The cross-section of Table 11 shows the influence of additives on rheological parameters and heating value of WCFS based on B4. At a solid phase content of 50 %, without additives, the structural viscosity is 1.84 Pa s, dynamic shear stress is 30.6 Pa, and heat of combustion is 3336 kcal kg^{-1}. Addition of 1.0 % NaOH + surfactant decreases structural viscosity to 1.76 Pa s, increases dynamic shear stress to 34.8 Pa, and increases heat of combustion to 3611 kcal kg^{-1}. Addition of 0.75 % $Ca(OH)_2$ + surfactant increases structural viscosity to 1.96 Pa s, decreases dynamic shear stress to 25.9 Pa, and increases heat of combustion to 3523 kcal kg^{-1}.

Based on these research results, it can be concluded that using $Ca(OH)_2$ as a stabilizing additive for the production of WCFS from brown and hard coals simplifies the process of their production, makes it more economical, and at the same time increases the stability and heating value of such mixtures.

CONCLUSIONS

Based on the presented data and conducted research on the rheological characteristics and calorific value of WCFS using different types of coal, the following conclusions can be drawn:

The solid phase content in WCFS has a significant impact on their rheological properties. When increasing the solid phase content up to a certain percentage value, the structural viscosity of WCFS remains almost unchanged.

Addition of sodium hydroxide (NaOH) and calcium hydroxide ($Ca(OH)_2$) to WCFS leads to the stratification of suspensions and formation of hard sediment. Low concentrations of these additives facilitate the coagulation of humic acids and convert the solution of sodium salts of humic acids into gel-colloids stabilizing the suspension of water and coal and reducing its viscosity.

The use of $Ca(OH)_2$ stabilizing additive in the production of WCFS based on brown and hard coal significantly simplifies and reduces the cost of the process while enhancing the stability and calorific value of such mixtures.

The results of the conducted research confirm the potential for improving the characteristics of WCFS based on high-ash content coals from Uzbekistan's deposits. These findings open prospects for utilizing WCFS based on these coals as highly effective fuels. The obtained information may be essential for improving the technological feasibility and optimizing production processes of such fuel mixtures, contributing to the increase of their energy efficiency and economic viability.

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