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Change in Grain-Size Composition of Lignite under Cyclic Freezing-Thawing and Wetting-Drying

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Abstract

The paper presents the change in grain-size composition of lignite under cyclic freezing-thawing (FTC) and wetting-drying (WDC). The article shows that in the spring and autumn periods the lignites can be subjected to repeated freezing-thawing and wetting-drying, which determines the possibility of changing their grain-size composition and structure. Experimental studies in laboratory conditions on the influence of cyclic freezing-thawing (FTC) and wetting-drying (WDC) on the quality indicators of lignites have been carried out, their granulometric (fractional) composition has been studied. Freezing-thawing cycle conditions are as follows (FTC): minimum exposure temperature: −20˚C; maximum: +5˚C; relative humidity: 30%; number of processing cycles: 3. Wetting-drying cycles are as follows (WDC): drying temperatures are +20, +40, +60, +80˚C, drying time 90 minutes, the coals are further subjected to rain (soaking) for a period of water saturation to humidity of 30% - 40% and dry again. The number of wetting-drying cycles is 3 times. The tests have revealed the destructive effects of FTC and WDC on the samples of lower metamorphic grade coal, and the cycles of wet-dry lead to the much higher yield of fine sizes (−6+0; −13+0 mm) than the cycles of freeze-thaw. Furthermore, it is found that the increase in the yield of fines depends on the heating temperature: coal disintegration proceeds more intensively at a higher temperature of drying.

Keywords

Lignite, Freezing-Thawing Cycle, Wetting-Drying Cycle, Grain Size Composition, Dust Coal, Storage, Loss, Quality

1. Introduction

Heat generation in the remote areas of the Far North (Russia), which are undersupplied in terms of energy and transport, uses different-grade coals. Coal handling services involve multi-chain logistics, with long-term warehousing and multiple transloading. As a consequence, coal delivered has a worse quality than coal initially shipped, and features high loss and great content of fines. The problem is particularly acute in the Arctic areas of the Republic of Sakha (Yakutia) as mining sites occur far from consumers, at distances of more than 1000 km, and coal supply involves complex logistics. The coal delivery terms may vary from 3 - 4 months to 2 years in this case, and the fuel loses its properties and qualities during this time period. In the open air, coal, especially lignite, gets weathered, dehumidified, cracked and broken into a large amount of fines [1] [2] [3]. The external factors which accelerate oxidation of coal in storage are rainfalls and temperature fluctuations (depending on season and time of day). According to [4], rainwater brought by the polar winds contains fewer peroxides than rains which come with the southern winds. Oxidation of coal during mining, storage and haulage degrades coal quality. Oxidation appears and develops in coal under the influence of circulation of air and moisture.

Evaluation of a lower metamorphic grade coal as a case-study of 2BR grade lignite from Kangalass field showed that the conditions and duration of storage affected the coal quality. Primarily, this relates to the grain-size composition which generally changes toward an increase in percentage of fine sizes. In open storage of ROM and graded coal in bulk, the grain-size composition of coal experiences a dynamic increase in amount of fines 0 - 10 mm in size—up to 30% [2].

Long periods of accumulation, storage and shipment of coal result in its physicochemical oxidation, weathering and degradation [5] [6]. Effects of these processes depend on grading of the starting crude, natural environment and climate in the areas of production and use, additional humidification, oxygen flow rate to coal, piling procedure and storage conditions [7] [8] [9]. Coal usability in small-scale power generation in hard-to-reach areas (fluidized bed combusting boilers) is governed by such coal qualities as: ash content, moisture as received, specific heat, volatile yield, grain-size composition and content of toxic impurities. Different fuels have different periods of storage, and the shortest periods are typical of peat and lower metamorphic grade coals (lignite, long flame coal).

In the case of layer burning, coal particles of less than 8 - 10 mm are often not actually involved in the combustion process, as part of them falls into the ash compartment, and part with the flow of hot air is carried to the chimney. The use of coal with a high content of fine fractions instead of varietal leads to reduced efficiency of boilers and over-consumption of coal. When burning in grilles boilers to produce the same amount of heat from coal, coal needs to be up to 1.5 - 2 times more than sorted coal [10] [11] [12].

From the studies on changeability of coal qualities during mining, storage and transportation, it is possible to suggest that coal perishes drastically while passing through all these stages of the process flow in the Extreme North.

When transported across different climatic zones and stored in different conditions, coal often experiences cyclic thermal influence of positive and negative temperatures. Such impact leads to the change in the mechanical characteristics and useful qualities of coal [6] [13].

Since the mid-20th century, the scientific community has accumulated extensive experience in determining how temperature affects the mechanics and quality of coal and other rocks.

Russian researchers show that cyclic freezing-thawing changes fractured porous structure of lignite. Under increased number of freeze-thaw cycles (FTC), high heat value of coal changes (ash-free dry mass). Furthermore, cyclic freezing and thawing of lignite reduce the content of total moisture of the fuel and especially moisture of analysis sample. It is found that the low heat value of lignite jumps, which, generally, may be connected with the drop in the moisture content of the material [13] [14]. Cyclic freeze-thaw also promotes cracking, which affects the mechanical characteristics and useful qualities of coal.

The study of the freeze-thaw effect on porosity of coal showed that porosity of all selected samples substantially grew [15].

The scope of the research embraced also the effect of wetting-drying cycles (WDC) on the physical and mechanical properties of coal. For example, it was found that cyclic wetting-drying had greater impact on the coal microstructure and mechanics than continuous wetting [16]. Wetting-drying cycles can result in progressive and irreversible structural damage of coal. Kunyou Zhou *et al.* [17] analyzed experimentally the mechanical behavior of coal samples in saturation with water and demonstrated that with the increase in water saturation, the uniaxial compression strength and the elastic modulus reduced, while Poisson's ratio grew. Zhizhen Zhang *et al.* [18] arrived at a conclusion that with the increased number of wetting-drying cycles, the mechanical properties of rocks (argillite) degraded.

Many recent studies focus on the effect of FTC on the sorptive capacities, mechanical behavior and qualities of coal. However, the influence exerted by FTC and WDC on coal quality, and the comparison of the FTC and WDC effects lacks scientific attention. The implemented review shows that only argillite is analyzed in this regard [19] [20], and there are studies on failure of sedimentary rocks under repeated freezing and thawing, and under repeated drying and wetting in a cold region. The impact of WDC on the rock strength was almost the same as the impact of cyclic freezing and thawing.

On the other hand, there is no research on the influence of FTC and WDC on the grain-size composition of coal. Considering the fact that coal goes to the Arctic areas of Yakutia along a multichain logistic framework, with long periods of interim and general storage, and experiences cyclic freeze-thaw, wet-dry, weathering etc., it is possible to state that the grain-size composition of coal changes greatly in the end.

This study aims at determining the effects of FTC and WDC on the grain-size composition of lignite via evaluation of formation of fines (−6+0) (dust coal) and (−13+0) on a laboratory scale.

2. Methods and Procedure

2.1. Original Data

The study object was 2B grade lignite sampled in Kangalass field located 45 km away of the town of Yakutsk. The size of the samples was selected based on the set tasks. With a view to having more reliable results after cyclic freeze-thaw and wet-dry, we selected the maximum size as per the existing state standard (GOST 2093-82 Solid Fuel. Sizing Analysis) [21]: C (coarse)—50 - 100 mm; N (nut)—25 - 50 mm, F (fine)—13 - 25 mm, as those size grades were the most suitable in terms of weathering, water saturation and basic qualities. Qualities of Kangalass coal presents in **Table 1**.

The test objective is to evaluate the influence exerted by cyclic wetting-drying and freezing-thawing on the loss of lignite by calculating how much coal transforms to fines −6+0 (dust coal).

Equipment involved in the sample preparation and lab-scale testing of the fraction composition of coal after cyclic wetting-drying and freezing-thawing was:

– electronic scales;
– a set of laboratory sieves;
– climatic cell TIRA-temp-NT7160;
– a sprinkler;
– a drying box.

Substantiation of sample size chosen for testing

Based on the set objectives and proceeding from the equipment capacities, and aimed to obtain more reliable results on the effect of FTC and WDC, it was selected to test samples of 30 kg. The distribution of size grades was as follows: coarse size 50 - 100 mm (C)—40%; nut size 25 - 50 mm (N)—30%; fine size 13 - 25 mm (F)—30%.

2.2. Experimental Procedure

1) Initial run-of-mine lignite (0 - 300 mm) from Kangalass Open Pit Mine, moisture content 15% - 30%.

Table 1. Qualities of Kangalass coal, upper seam, ES 0325-048-00161861-2004.

Seam	Water content mass W_t^r		Ash content A^d, %		Volatile yield V^{daf}, %	Average high heat value, kcal/kg		Mass fraction, % (not more)	
	avg	lim	avg	lim		Q_s^{daf}	Q_r^i	Rock mixed with coal	Total sulfur S_t^d
Upper	30.7	33.0	17.0	18.0	49.0	6700	3490	2.5	0.4

2) Coal is screened and graded per sizes (−100+50; −50+25; −25+13), and then coal is weighed in proportion of 40%, 30% and 30% per size grades up to the weight of 30 kg.

3) The resultant samples are divided into 2 groups for:

a) the cyclic wetting-drying tests and

b) the cyclic freezing-thawing tests.

All in all, there were 30 samples each having weight of 30 kg.

a) *Cyclic wetting-drying* (*WDC*)

For the WDC testing of a coal sample 30 kg in weight (12 kg—coarse particles, 9 kg—nut size particles, 9 kg—fines), it is required to ensure the sample coal moisture of 30% - 40% via wetting the sample using a sprinkler. After wetting, the sample is placed on a tray and is put in the climatic cell. The drying temperature is close to the real-life conditions of coal storage depending on the natural environment, climate and oxidation, and is +20˚C, +40˚C, +60˚Cand +80˚C. According to the state standard (GOST R 52911-2020) [22], the time of drying is 60 min for bituminous coal and 90 min for lignite. Before re-testing, the coal samples are subjected to wetting up to the moisture content of 30% - 40% and, then, to drying again. Experiments provided the number of 3 wet-dry cycles required for the fracture of the samples to become visible but yet not final (when the sample was crushed and powdered). After all cycles, the sample is removed from the climatic cells and the percentage of the size fractions −13+6 and −6+0 mm is determined by sieving according to GOST 2093-82 [21].

The WDC testing involved 24 coal samples, each weighing 30 kg.

All results were recorded and processed, and the effect of each cycle was evaluated.

b) *Cyclic freezing-thawing* (*FTC*)

A screening-formed sample of coal 30 kg in weight (coarse particles—12 kg, nut size coal—9 kg and coal fines—9 kg) is subjected to cyclic freezing and thawing. The coal sample is air-dried (moisture content 15% - 30%), the air humidity in the climatic cell during freezing is 35%. The coal sample is placed on a wooden tray and is frozen at +5˚C (GOST 32720-2014, GOST 10060-2012,) [23] [24]. The tests include 3 cycles as this is a period of reaching the optimal level of coal fracture, and this number agrees with the number of the wetting-drying cycles.

After all cycles completed, the sample is removed from the cell and is subjected to the sieve analysis (GOST 2093-82) to determine the percentage of the sizes −13+6 and −6+0 mm. All results were recorded and processed, and the effect of each cycle was evaluated.

2.3. Data Comparison and Estimation

According to the state standard (GOST 2153.2-84) [25], the number of test samples should be not less than 6 if the result reliability α is not less than 0.8 and relative error ε is not higher than 20%, and the number of test samples should be not less than 10 if the result reliability α is not less than 0.95 and relative error ε is not higher than 10%. The rated deviation, subject to the preset reliability, is 1.96 at $\alpha = 0.95$. The allowable error is 10% - 15%. The variation factor ranges as 15% - 20%.

The testing accomplished, the results are entered in electronic worksheet, and bar charts are constructed to compare the yields of the sizes −13+6 and −6+0 (dust coal) which are the loss of power station coal in fluidized bed combustion in thermal energy generation. Experimentation procedure for comparing WDC and FTC effects on grain-size composition of coal presents in Figure 1.

3. Results and Discussion

Table 2 compiles the data on the fraction composition of the solid fuel in storage under wet-dry and freeze-thaw. The data analysis shows that the yield of

Table 2. Grain-size composition of lignite after freeze-thaw and wet-dry cycles (as against initial coal samples).

Size grade	Yield in initial sample, %	Yield after FTC, %	Yield after WDC, %			
			dry T +20	dry T +40	dry T +60	dry T +80
−100+50	40	29.87	28.18	27.62	28.78	22.99
−50+25	30	28.78	20.58	24.80	20.47	15.70
−25+13	30	28.82	28.54	27.26	27.01	23.82
−13+6	0	7.87	13.61	11.70	12.31	19.52
−6+0 (dust)	0	4. 7	9.09	8.61	11.44	17.97

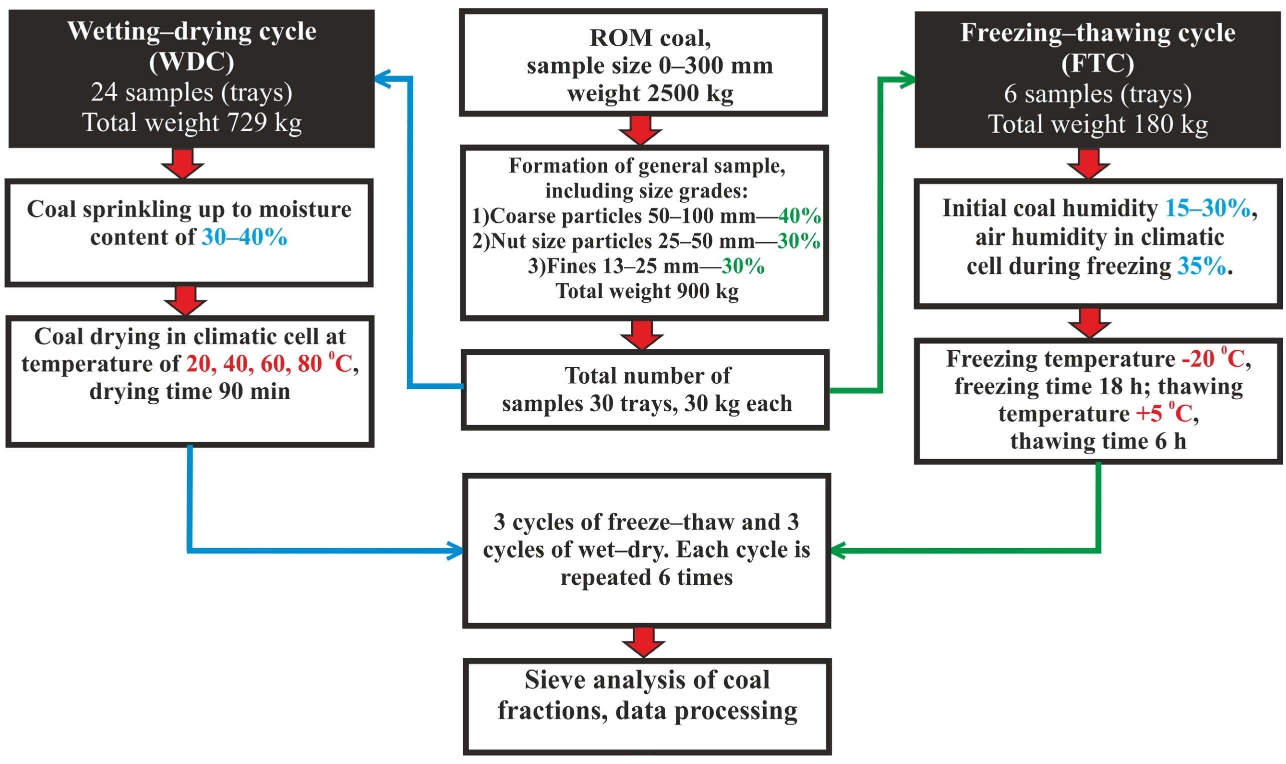

Figure 1. Experimentation procedure for comparing WDC and FTC effects on grain-size composition of coal.

fines after FTC is somewhat lower (4.67%) than after WDC (yield of size grade −6+0 is 9.09% at the drying temperature of +20˚C; 8.61% at +40˚C; 11.44% at +60˚C; 17.97% at +80˚C).

It should be mentioned that during the WDC tests of lignite with the increase in the drying temperature from +20˚C to 80˚C, we observe:

– the increase in percentage of fines (−6+0) from 9.09% to 17.97%;
– the decrease in the yield of coarse particles (−100+50; −50+25; −25+13) by 22% and the increase in the yield of fines by 9.09% at the drying temperature of +20˚C;
– the decrease in the yield of coarse particles (−100+50; −50+25; −25+13) by 19.1% and the increase in the yield of fines by 8.6% at the drying temperature of +40˚C;
– the decrease in the yield of coarse particles (−100+50; −50+25; −25+13) by 23.3% and the increase in the yield of fines by 11.43% at the drying temperature of +60˚C;
– the decrease in the yield of coarse particles (−100+50; −50+25; −25+13) by 36.9% and the increase in the yield of fines by 11.43% at the drying temperature of +80˚C.

Coal contains numerous microcracks and pores which facilitate inlet of oxygen and moisture. In coal having higher density and smaller diameter pores, the diffusion factor of oxygen is lower. Moisture, when it gets in cracks and pores, breaks coal. Lignite in the described tests features an increased content of moisture and, therefore, is sensitive to mechanical weathering. In the meanwhile, according to [4], oxidation of coal is mostly a surface phenomenon which only involves a small fraction of coal substance.

The particle size determination in lignite during storage under WDC and FTC shows much greater increase in the amount of +0−6 size under the WDC impact, and the other qualities are comparable with the initial data (**Figure 2**).

Longer influence of WDC on lignite induces a notable increase (to 18%) in the yield of fines −6+0 (**Figure 3**).

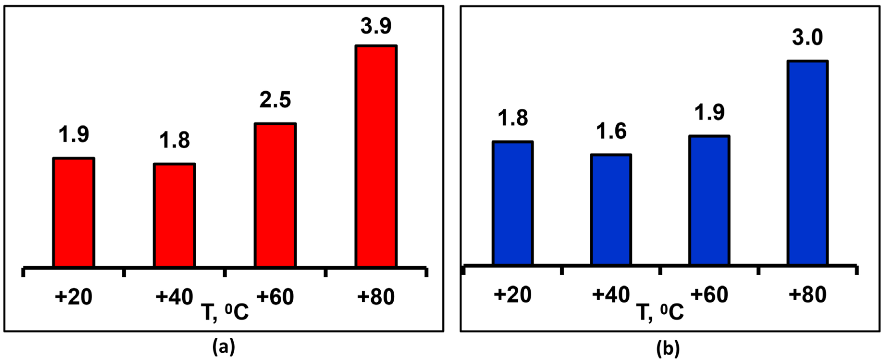

Figure 2. Comparison of grain-size compositions in lignite after cyclic treatment by freeze-thaw and wet-dry on laboratory scale: (a) stronger WDC effect as against FTC effect coal grade: yield of size −6+0; (b) stronger WDC effect as againts FTC effect coal grade: yield of size 13+0.

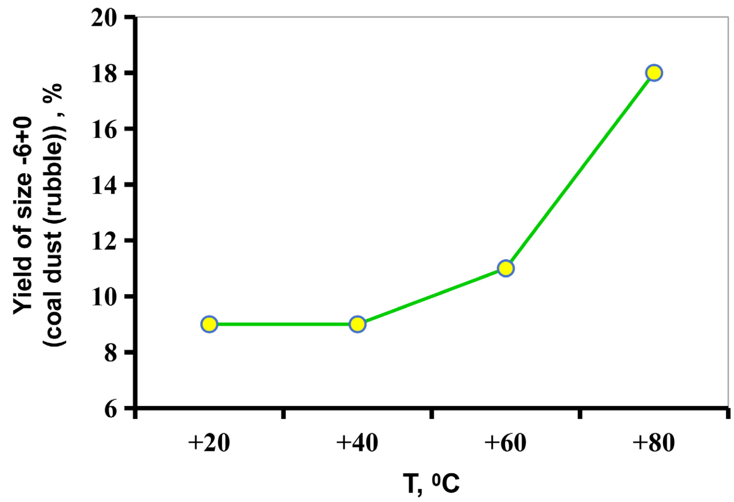

Figure 3. Fines yield versus drying temperature.

After heating at 60˚C, the further increase in the temperature leads to a jump in the yield of fines as coal fails quicker. It can be stated that the critical temperature for coal loss in the form of dust ranges as 60% - 65˚C.

It is very important to find the maximum temperature of coal storage without its loss and degradation.

As a result of processing and analysis of the test data on the yield of sizes −6+0 and −13+0 mm, the bar charts were constructed to compare the effect of FTC and WDC on coal in storage under different climatic conditions. It is found out that under WDC at the drying temperatures of 20% - 60˚C, disintegration processes run in coal 1.5% - 2.5 times more intensively than under FTC. For another thing, at the drying temperatures of 60% - 80˚C (WDC), the disintegration activity in coal grows even higher (by 3% - 4 times) as compared with the FTC effect.

The general factors that influence the coal quality as follows: origin, composition of the initial coal formation material, structure of the coal substance, presence and nature of mineral impurities, petrographic composition, humidity and conditions of coal storage. Destruction of coals at low temperatures is relatively slow. As temperatures rise, the rate of destruction of coals increases. Long-term storage of coal with temperature differences and conditions of its storage is accompanied, mainly, by the destruction of its pieces, the number of cracks and an increase in the amount of coal fines. There are numerous microfractures and pores in the pieces of coal, which facilitate the flow of oxygen and moisture into the inside of the piece. Moisture gets into the cracks and pores of a lump of coal, destroys it.

The preservation of coal, namely its grain-size composition during storage in the Far North, requires measures and methods to reduce the level of destruction of the environment (weathering). For maximum preservation of the original grain size composition of the coal extracted, it is recommended to store it at constant negative temperatures. Sorting and primary processing of coal with subsequent forming into bags also contribute to improved conservation. It is advisable to use open canopies, flooring, closed and buried warehouses, shielding from the direct impact of weathering.

4. Conclusions

The conclusions drawn after the experimental research are listed below.

1) Coal delivery to the Arctic areas of the Republic of Sakha (Yakutia) takes a long time (to 2 years) and involves an impact exerted on coal by wetting-drying, freezing-thawing, etc., which alters the coal quality, in particular, its grain size composition.

2) The lab-scale tests have been carried out to find the influence of WDC and FTC on the yield of dust fines (−6+0) for lower metamorphic grade lignite. It is shown that the influence of wetting-drying on the formation of fines (−6+0) is much higher than the effect of freezing-thawing.

3) The increase in the yield of dust fines (−6+0) depends on the heating temperature of coal: the higher drying temperature induces more intensive disintegration processes in coal.

4) The disintegration effect of the test cycles on the grain-size composition γ in 2B grade coal can be described by the inequality: $\mathrm{FTC}_{2B}^{\gamma} < \mathrm{WDC}_{2B}^{\gamma}$.

5) The impact of rainfall in combination with positive temperatures in the warm seasons results in substantial deterioration of coal quality (grain size composition) during coal product shipment to remote consumers in the Arctic areas.

6) Preservation of useful properties of solid fuel in the conditions of the Far North of Russia requires shielding of produced coal (stored or shipped in bulk), especially from the impact of rainfall.

Authors' Contributions

Natalia S. Batugina: Conceptualization, Methodology, Writing—original draft, Supervision; Vladislav I. Fedorov: Methodology, Writing—original draft, Supervision, Formal analysis, Investigation.

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Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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