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Experimental studies of the joint process "hydrotransport – oil agglomeration of coal"

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Abstract

Purpose. Development of highly effective dewatering methods along with preservation of technological properties of hydro-transported coal is one of the key tasks for improving modern pipeline hydrotransportation systems. Accordingly, the purpose of this study is to develop the models of "pressure loss in the pipeline – hydrotransport velocity" $i = f(V)$ for the "water-coal-fuel oil" mixtures of different compositions, which reflect regularities of the combined process of "hydro-transport – oil agglomeration of coal".

Methods. Physical modelling of the combined process of "hydrotransport – oil agglomeration of coal" was conducted under the test-field conditions involving specialized hydrotransport installations, i.e. a coal oil granulation stand and a hydraulic study stand. Relying on the experimental data, the trend curves were constructed, for each of which corresponding polynomial functions were determined.

Findings. In terms of test field, experimental dependencies of head losses in the pipeline $i = f(V)$ for the water-coal-oil agglomeration slurry were obtained based on the processing of the resulting family of statistical models for a hydrotransportation process of the indicated slurry.

Originality. For the first time, polynomial regularities have been obtained that demonstrate the dependence of head losses in the pipeline $i = f(V)$ on the composition and structure of solid and liquid phases of the water-coal-oil-agglomeration slurry.

Practical implications. The research results can be used while developing the combined technology "hydrotransport – oil agglomeration of coal" and for designing corresponding industrial or main coal pipelines.

Keywords: *hydrotransport, coal, oil agglomeration, modelling, test hydrotransportation system*

1. Introduction

1.1. Statement of the problem

Mining industry plays an important role in the development of the fuel and energy complex of any state, and particularly in the Ukrainian one. Unfortunately, today, mining and concentrating enterprises engaged in the extraction and processing of various types of minerals are in a state of prolonged crisis [1], [2]. Technical re-equipment of enterprises is the way out of this crisis.

The improvement of transportation systems is an integral part of this process as all production stages at mining and concentrating plants are linked to transportation [3]-[5]. An industrial transport system includes all types of transport, forming a transportation network, and specific types of transport. The main types are railroad, motor, and pipeline transport. Specific types of transport play a special role. These primarily include continuous-action transport, such as pipelines, conveyors, cableways, and monorails, as well as pneumatic and hydrotransport.

One of the directions for improving industrial and mainline hydrotransport for coal, oil, and hydromixtures of bulk materials is the development of pipeline transport. Hydrotransport is characterized by continuity and uniformity of cargo flow, increased reliability, possibility of full automation, independence from weather conditions; it has economic advantages over rail transport, especially when mines are located within remote areas; it generates less noise; it has significantly lower transportation losses and a reduced environmental impact; and it has shorter construction timelines [6]. Due to these advantages of hydrotransport, pipelines are used for transporting the following [6]-[8]: minerals (coal, sand, gravel, oil, salt solutions, etc.) from the extraction site to the consumer; waste from the concentrating plants; ash and slag from thermal power stations to dumps; and waste rock to piling.

Water is typically used as the carrier fluid. Hydromixtures of water and coal, crushed to a size of 0-1 (3-6) mm, are transported via slurry pipelines. The mass concentration of the slurry is 50% (the ratio of liquid to solid is 1:1). After

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transportation in the slurry pipeline, coal, both for coking and energy purposes, is usually dewatered. The main components of the coal pipeline are [8] (Fig. 1):

– main terminal, where coal is crushed and ground, a hydromixture is prepared and introduced into the pipeline system. This is also where the storage facilities and main pumping station are located;

– pipeline mainline with intermediate pumping stations along the route. Their location is determined by the topography of the area, type of slurry, and network conditions, which in general affect the head losses during hydrotransportation;

– blockage equipment (shut-off and blocking valves);

– receiving terminal – a dewatering complex for further use of coal.

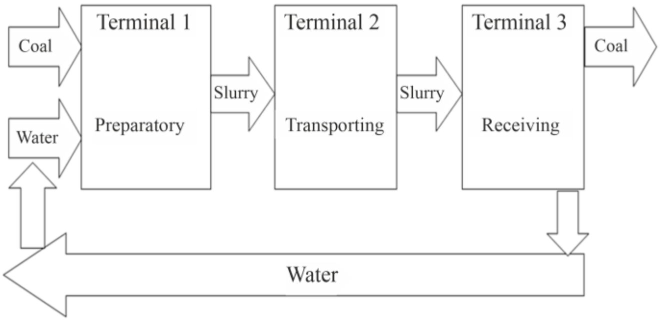

Figure 1. Principal scheme of a pipeline hydrotransportation system

Modern mainline hydrotransportation systems (MHTS) are transportation arteries in the external communications of enterprises, which can be part of either a regional fuel-energy or metallurgical complex, or an interregional centralized system for the delivery of raw materials and fuel. From the perspective of coal dewatering and concentration, the MHTS are of particular interest in terms of their granulometry, mechanisms, and specific nature of quality changes during hydrotransport. Regarding the optimal granulometric composition of coal for MHTS, different researchers propose following sizes: 6-0; 3-0; 2-0 and 1.2-0 mm [6]-[8]. Attention is focused on the content of fine fractions, which significantly affect hydraulic pressure losses during the movement of slurry in the pipeline, its stability during storage, and system shutdowns [9]-[11].

During hydrotransportation, additional grinding of coal occurs, depending on the physicochemical properties of the organic material and accompanying rock, initial coal size, and transportation distance. The coal particles subjected to hydrotransport acquire a rounded shape, which reduces their sorptive activity. The granulometric composition of coal at the receiving station of MHTS has a higher content of fine fractions, which is unfavourable for its mechanical dewatering, and in case of long distances (thousands of kilometres) makes dewatering unfeasible [12]-[14]. Studies [15]-[18] highlight the application of innovative materials and methods that contribute to the efficiency and sustainability of such systems.

For long-distance hydrotransport, the exposure of coal grades: non-baking (Nb), forge (Fo), fat (fa) gas (G) in water for 20 days increases the moisture content of the centrifuge cake by 1.5 to 4 times compared to the exposure for 20 minutes [19]. Hydrotransportation of coal grade Γ with a size of 2-0 mm over a distance of 250 km, under equal conditions, increases the moisture content of cake by 1.3 times. This effect is explained by the penetration of water into the pores of coal particles. It was also established that the dewaterability of freshly prepared slurry is indifferent to the action of polymer flocculants, which, under equal conditions, reduce the moisture content of hydraulically transported coal cake by 6-7% [20]. This is due to changes in the surface properties of the coal phase during hydrotransportation.

The loss of coking properties in coal during hydrotransportation is closely related to its mechanical changes. The transition of some coal into the < 0.5 mm size fraction alters the thermal zones of a coking process, which negatively impacts the coke strength. Additionally, changes in coking properties are associated with the following: alteration of the coal particle shape in a pipeline; coating of particles with fine, water-soaked clays, which increases the coke brittleness; and coal oxidation during the hydrotransportation process [21], [22].

Thus, following characteristics are typical for MHTS in the coal industry.

1. During the concentration and preparation of slurry, its storage in tanks, and hydrotransportation, the surface properties of coal experience certain changes, its capillary moisture increases, and it is further ground, which negatively affects the effectiveness of dewatering by mechanical methods. Factors of grinding, oxidation, and changes in coal particle shape as well as the swelling of the surrounding rock, reduce technological properties of coal for coking.

2. Sieve composition of coal for MHTS is selected based on optimizing a hydrotransport process, without considering the parameters of slurry dewatering.

3. At the main and hydrotransportation terminals of MHTS, there are no means to preserve the initial dewaterability and coking properties of coal, and at the receiving terminal, there are no means to restore them. Moreover, coal grinding in the pipeline and deterioration of its dewaterability and coking properties increase along with the transportation distance.

Thus, the development of highly efficient dewatering methods and preservation of the technological properties of hydraulically transported coal is one of the main tasks for improving modern MHTS. One effective technology that eliminates all the mentioned disadvantages of coal MHTS is the combination of hydrotransport and oil agglomeration of coal.

1.2. Literature review

A combined process of "oil agglomeration – hydrotransport" is a technology that integrates a process of oil agglomeration with transporting slurry in a hydrotransportation system. Its distinguishing feature is that the aggregation process occurs directly during transportation, without any additional equipment and devices.

Papers [23]-[30] deal with various aspects of a technological process of oil agglomeration of coal for its processing and beneficiation. In particular, papers [23], [24] describe the results of systemic studies by Ukrainian and Japanese scientists on the process of oil agglomeration of coal with different degrees of carbonization under various operational parameters, i.e., temperature, turbulence of the water-coal-oil mixture, its density. They also consider the use of various binding oil agents, such as petroleum products and coke chemical resins.

As a result of research [25], rational and optimal pelleting regimes for coal were found, leading to the formation of coal-oil agglomerates and granules with different structures: oil-filled, of the "core (large grain) – shell (small grains)" type, and others. Studies [26], [31], [32] determine that a mechanism of contact between agglomerate-forming objects includes following phases: the "meeting" phase is the one, which key factors include the size of meeting objects (coal grains and reagent droplets), the Re number, with the location of objects (in the core of the flow or in the boundary layer), coal and liquid densities, and kinematic viscosity; the "approaching" phase with the influencing factors of properties of the objects, which determine the sign and magnitude of the disjoining pressure, pH factor, presence of surfactants, temperature of the aqueous medium, temperature difference between the environment and agglomerate-forming objects, and shape of the coal particles; the "breakthrough of the water film" phase, which significant factors are the same as those for the "approaching" phase, with the addition of the relative speed of the objects, their mass, and water viscosity; and the "spreading" phase where the viscosity of oil (binder), accompanying chemical "reagent-coal" interactions, surface tension gradient of the oil, volume of the oil droplet, and kinetic energy of the agglomerate-forming objects are all important. The multifactorial nature of the contact process complicates significantly its efficiency calculation. However, the conducted research provides the basis for a targeted search for methods to intensify selective aggregation of coal.

A number of studies are dedicated to investigating the process of oil agglomeration of various types of coal, such as lignite [27], i.e., lignite from Rajasthan deposits in India [28], coal from Fujian Province in China [29], and coal from Duki region in Balochistan Province, Pakistan [30], among others. For each type of coal, characteristic effective operating parameters for oil agglomeration concentration were identified.

Papers [33]-[36]highlight various aspects of coal hydrotransportation and dewatering. In particular, study [33] examines the impact of hydrotransport on the electrokinetic properties of coal. It was found that the zeta potential of hydraulically transported coal increased, indicating hydrophilization of its surface. Study [34] identifies significant negative changes in the technological properties of coking coal during long-distance (500 km or more) hydrotransportation such as considerable deterioration in coal dewaterability and decrease in its caking ability, evaluated by a free swelling index and thickness of the plastic layer. The observed deterioration in the coking properties of coal due to its hydrotransportation has prompted the search for methods to reduce or completely avoid this effect. In paper [35], infrared (IR) spectroscopy was used to study changes in the surface properties of coking coal during long-distance hydrotransportation. The study revealed that coal undergoes oxidation during hydrotransport, leading to the leaching of soluble components, particularly phenolic compounds, into the aqueous phase. The action of water on pyrite inclusions and carbonaceous argillites catalyzes redox reactions involving metal compounds. As a result of the research, the authors of study [36] also identified other reasons for the change in technological properties of coking coal during long-distance hydrotransport, including redistribution of petrographic components of coal by size fractions.

Thus, long-distance hydrotransportation results in coal grinding during its transportation, changes in the surface characteristics of the organic material, and affects negatively its technological properties. At the same time, combined technological processes [37], [38], which enable a positive synergistic effect, are considered promising. In these processes, aggregation occurs under the influence of hydrodynamic forces generated in the turbulent flow of the liquid [39]-[41]. Turbulence is maintained by the transportation mode itself; however, it can be intensified through various obstacles, i.e. valves, elbows, pumps, bypasses, etc. Sometimes, impellers and internal static mixers are used. This combined technology was proposed in the 1980s in Japan [42] and, concurrently, in Ukraine [43].

It should be noted that the combined technological processes offer significant advantages over non-combined ones, such as lower energy consumption, simpler technological schemes (fewer machines and devices), environmental benefits, more.

1.3. Singling out of the previously unsolved problems

The analysis of research and publications shows that the study of the combined process of "hydrotransport – oil agglomeration of coal" is a relevant scientific and technical challenge. As a result of the analysis of the "oil agglomeration – hydrotransport" technology, it was demonstrated that the main unsolved problems of this process are the study and modelling of the factors affecting the efficiency and selectivity of coal aggregation. Directed search for ways to intensify the selective coal aggregation is one of the tasks in solving this scientific and practical problem. The complexity of the task is substantiated by the multifactorial nature of the process of contact between coal particles and oil. The study of the patterns of the combined "hydrotransport – oil agglomeration of coal" process is proposed to be carried out by physical and mathematical modelling of this process.

1.4. Formulation of the purpose and statement of the task

The goal of this work is to obtain polynomial models of the "pressure loss along the pipeline – hydrotransportation velocity" relationship, $i = f(V)$, for the "water-coal-fuel oil" mixture of varying composition, which reflect the patterns of the combined "hydrotransport – oil agglomeration of coal" process.

To achieve this goal, it is necessary to conduct physical modelling of the combined "hydrotransport – oil agglomeration of coal" process under the field conditions using a specialized hydrotransport installation. Based on the experimental data from the physical model, the patterns of the combined "hydrotransport – oil agglomeration of coal" process will be determined.

2. Materials and methods

Physical modelling of the combined "hydrotransport – oil agglomeration" process was carried out on the oil granulation coal stand and the hydraulic study stand. An oil granulation process was implemented on a batch-operated stand, which includes a turbine mixer and auxiliary devices and equipment (Fig. 2). The mixer is equipped with an electric drive that allows for adjusting the shaft rotation speed within the range of 0-70 s^{-1}. A working chamber of the mixer is a removable cylindrical vessel with a volume of 1.0-5.0 litres. An impeller is removable, with either a four-blade design or a "squirrel wheel" type. The diameter of the impeller is 3/4 of the diameter of the working chamber. The height of the "squirrel wheel" impeller is 2/3 of the chamber height. A gap between the impeller and the chamber bottom the is 0.5 cm. The chamber is equipped with a thermostat. The binder was introduced into the coal-water mixture using a syringe dispenser. The agglomeration product was dewatered on a stationary sieve with mesh sizes of 0.1 and 0.3 mm, or in a centrifuge.

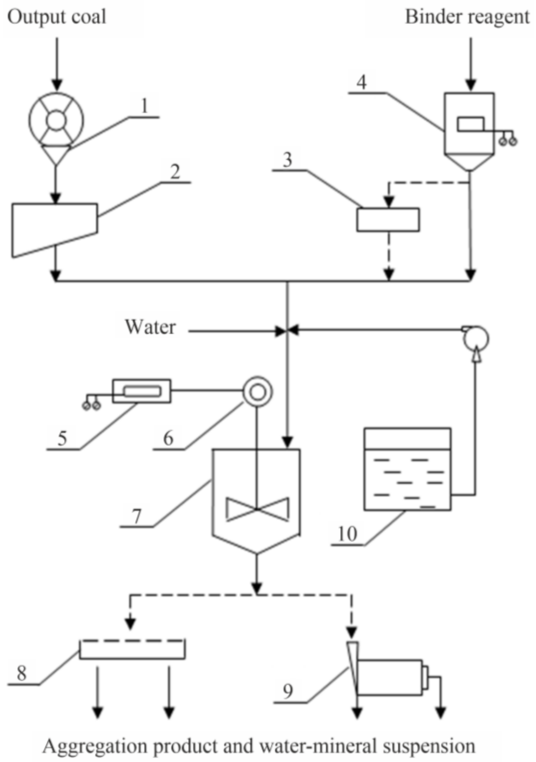

Figure 2. Schematic diagram of the laboratory setup for oil agglomeration of coal: 1 – hammer crusher; 2 – raw material hopper; 3 – emulsifier; 4 – reservoir for binder with electric heater; 5 – speed variator; 6 – motor; 7 – working chamber of the impeller mixer; 8 – sieve; 9 – centrifuge; 10 – environment regulator container

A process of hydrotransportation of coal and coal-oil agglomerate was carried out on a hydraulic study stand (Fig. 3).

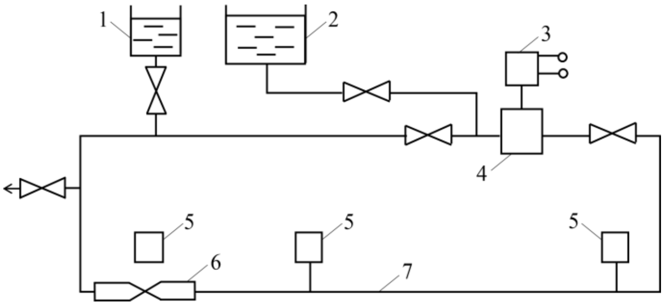

Figure 3. Schematic diagram of the experimental setup for hydrotransportation of coal, the "water-coal-M100 fuel oil (coal-oil granulate)" mixture: 1 – hopper; 2 – support vessel; 3 – drive; 4 – pump; 5 – differential manometers; 6 – Venturi pipe; 7 – measuring section

The conditions for hydrotransportation of coal, the "water-M100 fuel oil-coal" mixture, and coal-oil granulate (agglomerate) were modelled in terms of the experimental closed hydrotransportation system. The system consisted of a glass pulp pipeline with a diameter of 100 mm and a length of 52 m, equipped with a centrifugal pump with a capacity of 60 m^3/h and a variable-speed drive. The slurry velocity was measured using a Venturi flow meter; specific head losses were measured using differential membrane manometers of DM type, installed on a straight horizontal section, being 14.5 m long.

Samples of the transported material (coal, coal agglomerate or carrying liquid medium) were taken using a special tubular sampler. The object of hydrotransportation was coal, coal-fuel oil granules produced on the plant shown in Figure 2, with the oil-binder content ranging from 15-23 wt.% as well as the "coal-granulate" mixture, which characteristics are provided in Table 1. The particle size distribution was measured using a method described in detail in [44].

Table 1. Characteristics of the output coal and coal-oil aggregates

Material under study	Grain-forming coal				Content of fuel oil in granules, Q_M, %	Granule size, d_a, mm
	Grade	Size, mm	Size class, mm	Percentage ratio		
Coal	Gas (G)	0-1.0	0.1	39.7%	–	–
Granules		0-1.0	0.1	39.7%	15	0.5-1.6
Granules		0-0.1	–	–	23	1.0-2.0
Mixture "coal-granulate"		0-1.0	0.1	39.7%	15	0.5-1.6

The procedure for modelling experimental data is described in detail in papers [45]-[48]. As a result of the modelling based on the experimental data, trend lines were constructed, and polynomial functions were determined for each of them. The polynomial smoothing method, implemented in Excel, allowed not only for the development of predictions but also for identifying trends in the obtained experimental data. This approach provided the opportunity for a deeper analysis of the results and enabled a more accurate assessment of the behaviour of the studied parameters.

3. Results and discussion

In this section, the research results are presented in the form of curves, which show the changes in values of hydrotransportation parameters along the distance L of hydrotransportation from 0.5 to 230 km. The experimental curves of pressure loss $i = f(V)$ are plotted depending on the slurry velocity V, along with key moments of structural changes in a solid granulate phase and characteristics of a liquid phase.

The experimental curves of $i(V)$, measured directly after loading coal and coal-oil granules (or an equivalent amount of M100 fuel oil) (for distances L = 0.5-2 km), are shown in Figure 4. As for the coal slurry, curves 3 and 4 for the slurry with concentrations of c = 18%, 50% exhibit a consistent pattern – pressure losses $i(V)$ across the entire velocity range V are practically parallel to the curve $i(V)$ for water and increase systematically with the increasing c. A non-trivial result was observed for the water-granulate mixture – here, a pressure loss reduction effect was recorded for the water-granulate mixture $i(V)$ as the velocity V increased (curves 2, 5 for granules c = 5 and 10%). Moreover, for V > 1.9-2.0 m/s, the pressure losses for the granulate slurry become lower than those for water.

At first glance, this seems like a paradoxical result, which required additional investigation. After several duplicate experiments and confirming the stable repeatability of curves 2 and 5 for the granulate with c = 5%, 10%, a sample of granules and the liquid (carrying) phase was taken.

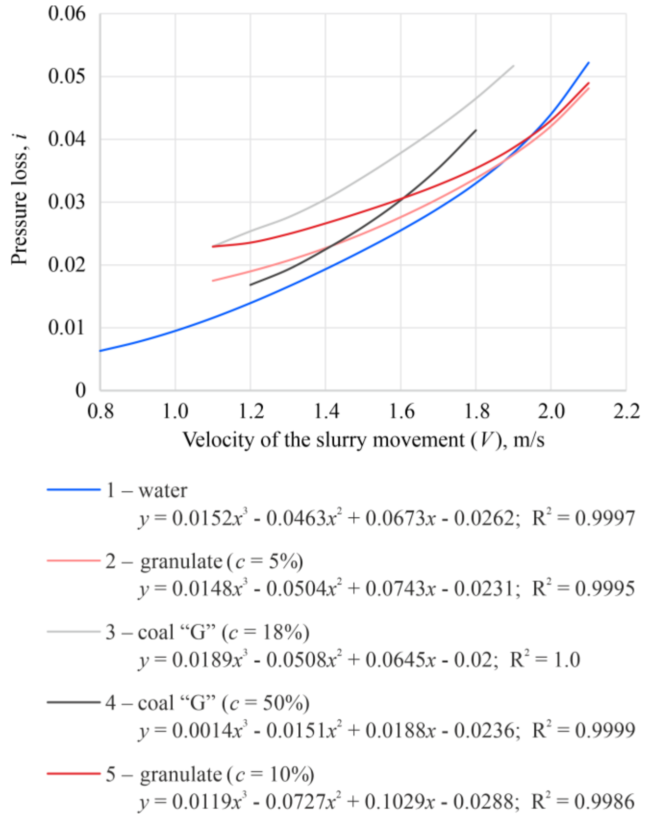

Figure 4. Approximated curves based on the experimental data for hydrotransportation of coal-oil granules and obtained immediately after loading the granules, measured at a distance of L = 0.5-2.0 km

Granule cross-sections (Fig. 5a) revealed the presence of a binder-agent film on their surface, while microscopic studies of the liquid phase showed that it consists essentially of a coarse emulsion of the "oil-in-water" type (Fig. 5b). Moreover, the presence of oil droplets in the liquid phase emulsion increases along with the growing velocity *V* of hydrotransportation.

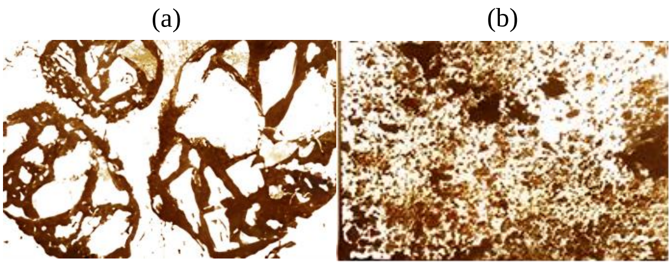

Figure 5. Microscopy of the solid and liquid phases of the slurry: (a) cross-sections of the original granules, d = 1.0-2.2 mm; (b) coarse dispersion emulsion of the "oil-in-water" type

Thus, it can be assumed that the observed phenomenon of partial detachment of oil film from the surface of the coal-oil granules during their hydrotransportation and dispersion of the detached oil films during slurry transportation in the turbulent regime, leading to the formation of the "oil-in-water" emulsion, is the thing resulting in non-trivial behaviour of the *i*(*V*) curves for the water-granulate slurry. The friction of emulsion layers is lower than that of the water ones, which explains the reduction in pressure losses for the water-granulate mixture and even the intersection of curves 2.5 for the granulate with *c* = 5, 10% with the *I* (*V*) curve for water.

The experimental *i* (*V*) curves taken at the 4 and 20 km sections, after loading coal, coal-oil granulate, and coal-granulate mixtures, are shown in Figures 6 and 7.

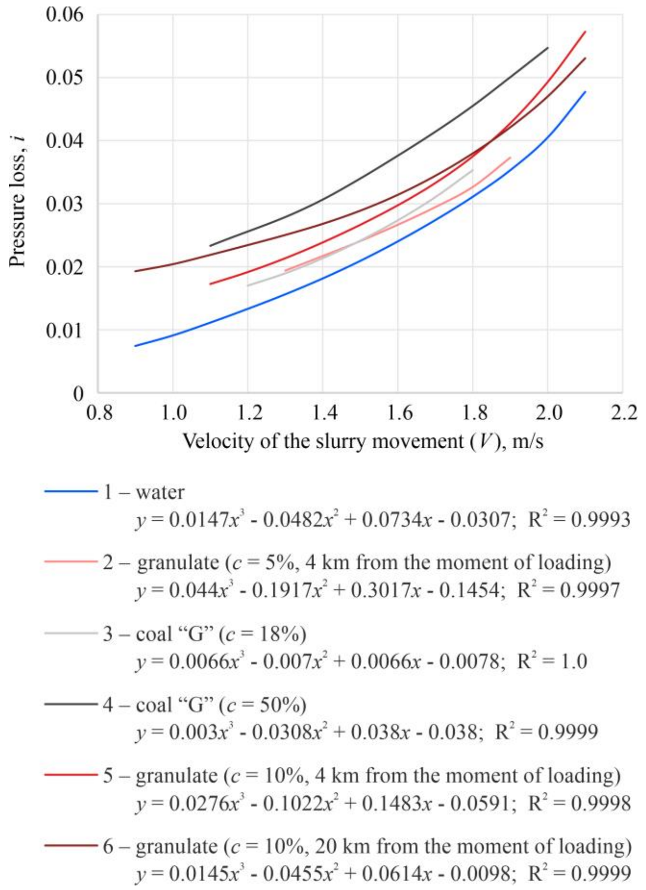

Figure 6. Approximated curves based on the experimental data for hydrotransportation of coal-oil granulate and recorded after the slurry passed through the distances of 4 and 20 km

In case of coal slurry at the 4 km section after loading, the head loss curves *i* (*V*) across the entire range of velocities *V* are practically parallel to the *i* (*V*) curve for water, with head losses increasing systematically with the growing *c* (curves 3 and 4, *c* = 18 and 50%). For the "coal – coal-oil granulate" mixture, the situation is somewhat different. For the slurry of granules, as the velocity increases, there is a tendency for curves *i* (*V*) to approach curve *i* (*V*) for water but not as rapidly as observed immediately after loading. It can be explained by instability of the "oil-in-water" emulsion and conglomeration of coal-oil granules during their hydrotransportation.

For the coal slurry at the 20 km section after loading, the character of head loss curves *i* (*V*) does not change. They remain practically parallel to the *i* (*V*) curve for water, with head losses increasing systematically with the growing *c* concentration (curves 4 and 5, *c* = 18 and 50%).

As for the granulate-coal mixtures at the 20 km section after loading, the behaviour of head loss curves *i* (*V*) is different. For slurries in which solid phase is dominated by granules rather than coal, the shape of curves *i* (*V*) is closer to that of pure water-granulate mixtures (curve 2). Conglomeration of granules in the "coal-granulate" mixture occurs very slowly (at 20 km, it is practically absent). The liquid phase is represented by the coarse "oil-in-water" emulsion (just like in pure water-granulate mixtures immediately after loading).

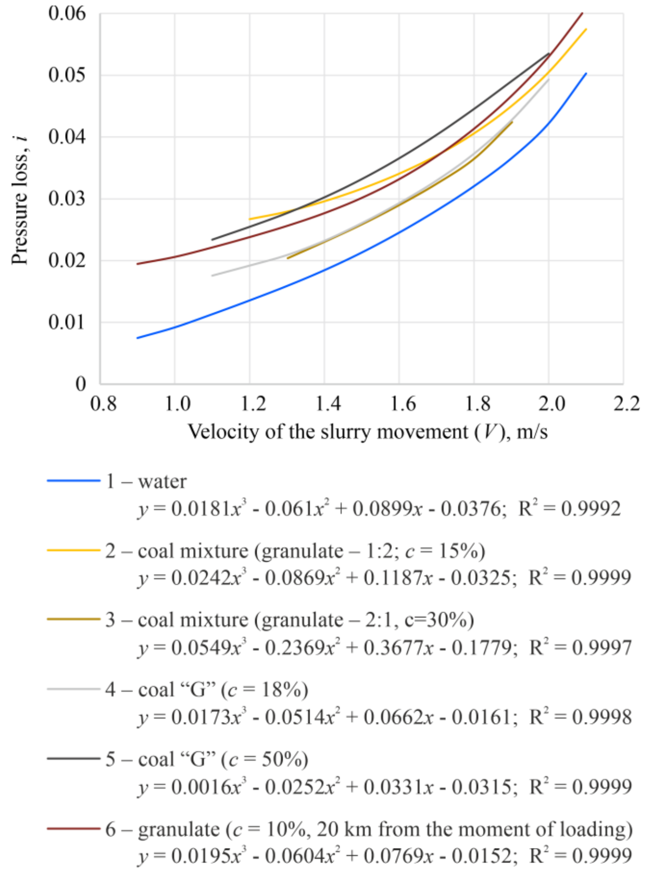

Figure 7. Approximated curves based on the experimental data for hydrotransportation of coal, coal-oil granulate, and coal-granulate mixture at the distances of 4 and 20 km

Therefore, even at the 20 km section of the hydrotransportation distance, the head loss for the "coal : granulate – 1:2" mixture with $c = 15\%$ at the point of $V = 2.2$ m/s is almost the same as the head loss for water. If coal predominates, the shape of curve $i\,(V)$ is closer to that of the pure coal-water mixture curves (curve 3).

In pure granulate slurries, the emulsion of "oil-in-water" formed in the first few kilometres of transportation breaks down, and the granules conglomerate. As a result of these phenomena, curve $i\,(V)$ flattens out and does not closely approach curve $i\,(V)$ for water across the entire range of working velocities. However, it does get somewhat closer to it as the slurry velocity increases (curve 6).

The experimental curves $i\,(V)$ recorded at the 30 km and 230 km sections after loading coal, coal-oil granulate, and coal-granulate mixtures are shown in Figure 8.

For the coal slurry at the 230 km section after loading, the pressure loss curves $i\,(V)$ across the entire range of velocities V do not change – they remain practically parallel to the curve $i\,(V)$ for water, and the pressure losses increase with the increasing c concentration (curves 5 and 6, c = 18 and 50%).

It should be noted that the curve $i\,(V)$ for the water-coal mixture with $c = 50\%$ is approximately the same at the distances of 20, 30 and 230 km, indicating that there are minimal changes in the granulometric composition of the solid phase, and there is practically no swelling of the coal under analysis. The behaviour of coal-granulate slurry (34% granules), $c = 50\%$, after 30 km of hydrotransportation is similar to that observed after 20 km. An attempt to modify the surface of coal and granules by adding kerosene to the slurry (1 kg/ton of dry coal) did not alter significantly the shape of curve $i\,(V)$.

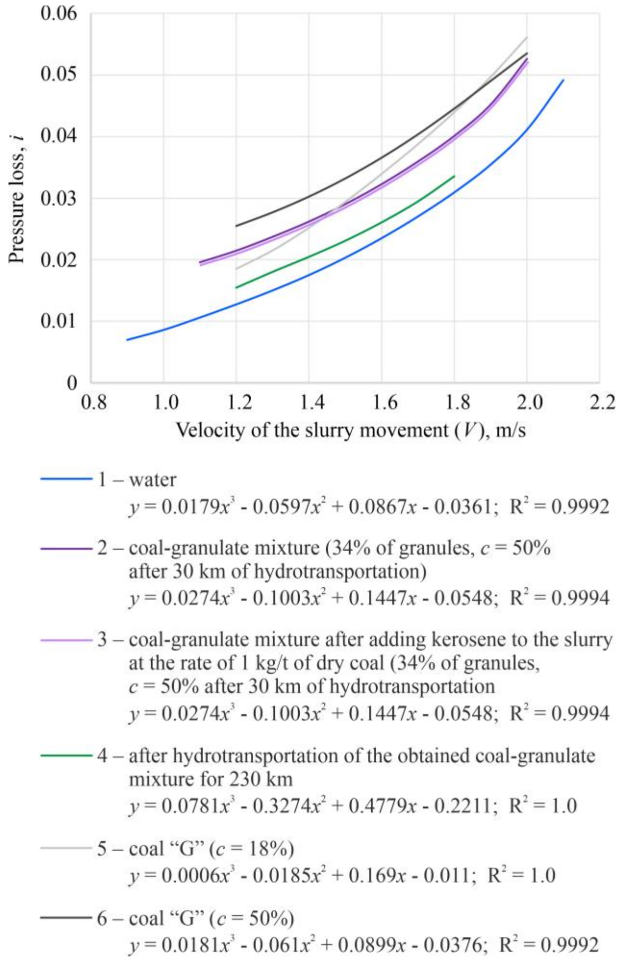

Figure 8. Approximated curves based on the experimental data for hydrotransportation of coal, coal-oil granulate, and coal-granulate mixture at the distances of 30 and 230 km

More substantial changes occur in the structure of the coal-granulate slurry (34% granules), $c = 50\%$, after 230 km of hydrotransportation. At this distance, the coal-oil granules being transported in the mixture with coal disintegrate, the initially unagglomerated coal becomes oil-coated, and new coal-oil structures form; these structures have thinner oil films, which then conglomerate (Fig. 9).

The coal-oil granulate undergoes several stages of structural changes during hydrotransportation, which affect the shape of the pressure loss curve $i\,(V)$. Eventually, conglomerates are formed, which are 2-3 times larger in size than the original granules, leading to a sharp increase in hydraulic pressure losses in the pipeline. Therefore, the increase in pressure losses within the working velocity range can be explained by structural changes in the solid phase.

Thus, the obtained data allow the following conclusions to be made:

1. Fundamental possibility of transporting coal-oil granulate and "coal-granulate" mixtures by hydrotransport has been confirmed, both over short (hundreds of meters, first kilometres) and long distances (hundreds of kilometres).

2. Process of redistribution of the binding agent between the coal and oil-granulate components of the slurry has been traced.

3. Coating of the initially non-granulated (non-agglomerated) coal during the joint hydrotransportation of "coal-oil granulate" causes an oil agglomeration process (additional agglomeration) of coal to occur directly in the pipeline.

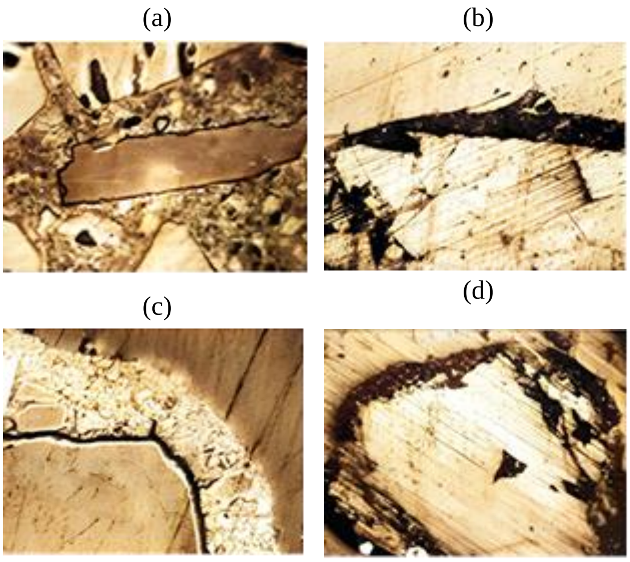

***Figure 9.** New coal-oil structures formed during the combined process of "hydrotransport – oil agglomeration of coal" directly in the coal pipeline after 230 km of hydrotransportation: (a) oil-coated coal; (b) oil boundary between coal grains; (c) coal grains covered by protective surface layers of small oil-coated grains; (d) agglomerates of "coal-oil"*

4. The pressure loss curves along the pipeline, which integrally reflect the flow characteristics of the slurry, are similar for both coal and coal-oil agglomerates. The initial velocity parameter for the coal slurry is slightly higher. However, the operational velocity zone, being equal typically to 1.1-1.2 times of the initial velocity, overlaps for both coal and coal-agglomerate slurry. This indicates that the oil agglomeration process has no negative impact on the rheological characteristics of the mixture.

Thus, for the first time, polynomial dependencies have been obtained that reflect the combined technological process of "hydrotransport – oil agglomeration of coal" and demonstrate the relationship of pressure losses in the pipeline $i = f(V)$, depending on the composition and structure of solid and liquid phases in the water-coal-oil-agglomerate mixture.

It has been proven that the coating of the initially non-granulated (non-agglomerated) coal during the joint hydrotransportation of "coal-oil agglomerate" leads to additional coal agglomeration immediately in the pipeline.

The combined process of "mainline hydrotransport – oil agglomeration" of coal should be considered as an optimal technology to ensure minimal fragmentation of the coal phase during hydrotransportation and minimize the impact of transportation distance on the coal dewatering process. At the same time, the granulation composition of coal is preserved by "blocking" the coal surface with an oil film, preventing physical and chemical destruction of that surface.

In the future, modelling the "mainline hydrotransport – oil agglomeration" process can be considered as a fundamental technical solution when designing MHTS for coal.

4. Conclusions

Physical modelling of the combined process of "hydrotransport – oil agglomeration of coal" has been carried out. The obtained experimental data demonstrate the fundamental possibility of transporting coal-oil granulate and "coal-granulate" mixtures hydraulically over both short (hundreds of meters, the first kilometers) and long distances (the initial hundreds of kilometers). A process of the binding reagent redistribution between the coal and oil-granulate components of the slurry has been traced experimentally. It has been shown that coating of the initially non-granulated (non-agglomerated) coal during the joint hydrotransportation of "coal-oil agglomerate" results in the occurrence of oil agglomeration process (additional agglomeration) immediately in the pipeline.

The obtained mathematical models describe the behaviour of the "water-coal-fuel oil-granulation" mixture during its hydrotransportation and can be used to regulate the combined process, predict the temporal boundaries of individual stages of coal oil agglomeration, and track its progress in the hydrotransport pipeline.

Author contributions

Conceptualization: VB, TO; Data curation: VB; Formal analysis: VB, TO, LS; Funding acquisition: VB; Investigation: VB, TO, SC; Methodology: TO, SF; Project administration: LS; Resources: VB; Software: SP; Supervision: TO, SP; Validation: LS; Visualization: SF; Writing – original draft: TO, SP, SC; Writing – review & editing: SP. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Експериментальні дослідження суміщеного процесу “гідротранспорт – масляна агломерація вугілля”

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Мета. Розробка високоефективних засобів зневоднення і збереження технологічних властивостей гідротранспортованого вугілля є одним з основних завдань із вдосконалення сучасних магістральних гідротранспортних систем. Відповідно, метою даної роботи є одержання моделей “втрата напору по трубопроводу – швидкість гідравлічного транспортування” $i = f(V)$ для водо-вугільно-мазутної суміші різного складу, які відображають закономірності протікання суміщеного процесу “гідротранспорт – масляна агломерація вугілля”.

Методика. Фізичне моделювання суміщеного процесу “гідротранспорт – масляна агломерація вугілля” проведено в полігонних умовах на спеціальних установках гідравлічного транспорту, а саме, стенді масляної грануляції вугілля та стенді гідравлічних досліджень. На основі експериментальних даних будувалися криві лінії тренду, для кожної з яких визначені відповідні поліноміальні функції.

Результати. В умовах випробувального полігону одержані експериментальні залежності втрат напору по трубопроводу $i = f(V)$ для водо-вугільно-масляно-агломераційної гідросуміші, на основі обробки одержано сімейство статистичних моделей процесу гідротранспорту вказаної гідросуміші.

Наукова новизна. Вперше одержані поліноміальні закономірності, які демонструють залежність втрат напору по трубопроводу $i = f(V)$ від складу та структури твердої і рідкої фаз водо-вугільно-масляно-агломераційної гідросуміші.

Практична значимість. Результати виконаних досліджень можуть бути використані при розробці суміщеної технології “гідротранспорт – масляна агломерація вугілля” та проєктуванні відповідного промислового чи магістрального вуглепроводу.

Ключові слова: *гідротранспорт, вугілля, масляна агломерація, моделювання, полігонна гідротранспортна установка*

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