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*Review*

# A Review of Methods, and Analytical and Experimental Studies on the Use of Coal–Water Suspensions

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**Abstract:** Research in the field of building mathematical models for combustion processes has been ongoing ever since the chemical reactions of combustion were first discovered. The authors of this review have systematized mathematical models of coal–water suspension (CWS) combustion processes, the sequence of analytical and experimental studies, and have also shown the global genesis of the CWS use. In addition, this review touches upon a topic that is inextricably linked with the combustion of CWS, namely their transportation from the place of coal mining to their place of thermal utilization. For developing countries, their own energy independence is in the foreground, as it is the basis for their economic independence and also a means for other sectors of their economy to be protected from the impact of market changes in fuel prices in the future spot world market. The authors of this review explored the possibility of using Kyrgyz brown coal and transporting it through a coal pipeline from a mountainous area to an industrial site for thermal utilization in specialized steam boiler units. As the economic analysis showed, for the conditions of the Republic of Kyrgyzstan, the use of CWS and coal pipelines with rising prices for natural gas is economically justified. The recommendations of the authors are used in scientific reports and methodological recommendations for the energy and mining sectors of the Republic of Kyrgyzstan, how the recommendations can also be applied to similar conditions in the highlands of Russia, China, and India.

**Keywords:** coal–water suspensions (CWS); combustion process; mathematical modeling; studies; transportation

**MSC:** 93A30



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## 1. Introduction

Mathematical models of solid and gaseous fuels began to be compiled by scientists in the first half of the 20th century, when the concept of the kinetics of chemical reactions were developed. Spaulding [1], Zeldovich [2], and Williams [3] presented detailed information on the mathematical modeling for the combustion kinetics of coal–water suspensions. The researchers emphasized that the efficiency of fuel combustion depends on the thermophysical characteristics of organic fuel [2], on the design of the burner [1], and—for solid fuel—also on the degree of grinding [3]. Verwey, Overbeck [4], and Furnas [5] laid the foundations for the mathematical description of the physical processes that occur during the combustion of colloidal mixtures, taking into account the size of the coal particles included in these mixtures. When burning liquid fuels, the forces of viscosity become important, and, for water-based suspensions, taking into account the forces of intermolecular attraction (i.e., van der Waals forces) allows one to create more accurate mathematical models for studying the combustion of coal–water fuels. Krieger and Dougherty [6], Takano, Cambe [7], Freiling [8], and Rutgers [9] all conducted rheological studies of suspensions and attempted to create prototypes for a mathematical description of the behavior of suspensions during their combustion. The rheology of suspensions is so unusual that individual branches and institutes have taken up the mathematical description, at low temperatures, of their behavior. Yufin [10] laid the foundations for the mechanization of coal and ore mining via the hydraulic method. Jvarsheishvili [11] and Tsarnat [12] determined the controlled technical parameters of hydromechanization. Further, the work of [13] shows the features of the operation of pipelines for transporting suspensions in winter. Similar developments are considered in [14], and in the article [15]. Volkov and Gokhman summarized the developments available at that time in the field of pipeline transport for transporting suspensions over long distances. In later works [16,17], Chinese scientists studied the freezing of ballast water in a mixture of coal ore. However, that which is of the greatest interest in this area are the studies of Li, Huang, and Lv [18,19], in which the authors studied the effect of low temperatures on the movement of water inside coals and the movement of suspensions. We note the works [20,21], in which the numerical simulation of the process of transporting suspensions at low ambient temperatures was carried out. At the same time, an experimental study was carried out in [22], and an attempt was made in [23] to mathematically model the processes presented in [20,21].

In Kyrgyzstan, in the 1970–1980s of the 20th century, a technology was developed for the disposal of dispersed coal sludge. This dispersed coal sludge was polluting the environment and is formed in the processes of enrichment, hydro-extraction, and transportation of coal from a mine using pipeline transport [24]. Mathematical models have been developed for these processes, such as in models to reduce environmental pollution [25], coal combustion [26], and transportation [27]. Due to the high stability and dispersion of sludge suspensions, significant costs are required for their dehydration [28]; further, direct combustion of sludge suspensions in thermal units would solve the problem of their disposal [24]. It was assumed that, under certain conditions, this could be more profitable and more technologically advanced than the combustion of dispersed coal released by dehydration and the drying of slurry suspensions [29,30]. In techno-economic calculations of the efficiency of direct combustion, it was assumed that the cost of coal sludge is small compared to other costs for their processing into a technologically acceptable fuel [31,32].

The development of the world economy and the steady upward trend in prices for petroleum products lead to an intensive search for new technologies for processing coals [33,34], the proven reserves of which are more than 20 times greater than those of oil. Currently, in such countries as China, Japan, Italy, the USA, Sweden, and Russia, special attention is paid to water–coal suspensions [35,36] as a real alternative to liquid fuels from oil. First of all, this is due to the significant scientific and technical potential accumulated by these countries in the field of production, transportation, storage, and the combustion of coal–water fuel (CWF) in boiler plants of thermal power plants, steam-gas, and gas turbines.

In China, for the technical guidance on the introduction of water–coal fuel [37,38], the State Center for Coal-Water Suspensions of the Coal Industry was established. In 2001, China consumed more than 2.0 million tons of such suspensions [39,40] per year. Fuel preparation was carried out at eight plants with a capacity of up to 600 thousand tons per year. The consumers were thermal power plants that previously operated on fuel oil, enterprises of the chemical, metallurgical, pulp and paper, and other industries. In the next 20 years, it is planned that the capacity for the production of CWF to 100 million tons per year [41,42] will be increased.

One of the ways to increase the generation of electrical and thermal energy by the fuel and energy complex of Kyrgyzstan is to increase the share of coal in the combusted raw materials. In the future, the increase in generating capacities will also be carried out at the expense of thermal power plants that operate on the low-grade coals of the Karakechi coal basin, as such the volume of consumption of these will increase annually.

A significant increase in the share of coal in the generation of heat and electricity in the Kyrgyz Republic requires the development of new energy and environmentally advanced technologies for the processing and burning of coal. One of the most economically justified and environmentally friendly types of fuel at large thermal power plants of the country and boiler plants is the use of suspension coal–water fuels.

It must be noted that preliminarily carried out deep demineralization of the solid phase of the coal suspension—via flotation methods—reduces the ash content of the fuel to 2–3%. According to the literature data [41,42], the conversion of demineralized coal into CWF with a fineness of less than 10 μm, will reduce the ignition temperature, which is about 500 °C for existing CWF. Transferring demineralized coal to an ultra-dispersed state with an average particle size of less than 1 μm will make it possible to bring the ignition temperature of the coal dispersion to the ignition temperature of diesel fuel (about 350 °C) and, at the same time, obtain the rheological properties of CWF close to those of diesel fuel [43]. This provides grounds to assume that a water–coal suspension based on coal in an ultra-dispersed state will have consumer characteristics close to conventional diesel fuel.

From the literature data [44,45], it is known that the presence of solid particles of a certain composition, concentration, shape, size, and other physicochemical and technological parameters in a liquid can significantly change, on the one hand, the initial properties of the liquid itself and, on the other hand, the properties of the filler. In this sense, the suspension is a liquid–microsolid-phase quasi-equilibrium system that has all the features of a classical composite material. Based on this, the suspension can be conditionally classified as a specific liquid-phase composite material with broad functional and technological capabilities, physicochemical, and consumer properties [44,45].

In known methods, the process of preparing various suspensions consisting of a mechanical mixture of a liquid phase (filler) is divided in time. In this case, the fractionation and dispersion of the solid product is carried out mechanically, and then it is mixed with the liquid matrix. In this case, the mixing process can be combined with the grinding of the filler, separation, and other processes. Such a sequence of actions reduces the efficiency of activation of the liquid-phase matrix by solid filler particles [44].

The functional activity of various liquids can be controlled by varying the pressure of the flow with particles, the size of the fractionation vessel, the number of fractionation stages, the diameter of the nozzle for the microheterogeneous phase, and other technological parameters of the entire process [43,46]. Thus, hydro percussion, multi-stage fractional technology makes it possible to combine the processes of formation of a highly dispersed solid phase and suspension as a whole, and to increase the functional activity of the latter.

The positive parameters of the proposed method for obtaining activated carbon suspensions include easy process controllability, production of suspensions on an industrial scale, and no restrictions on the strength characteristics of the solid phase.

The main activating factor of the proposed hydro-percussion method for obtaining activated suspensions based on highly dispersed coal particles should include the following:

- a formation of highly dispersed coal particles after multiple fractionations, directly inside the liquid matrix;
- a developed (large) surface of coal particles;
- an impact on the liquid of mechano-chemical, physical, and other processes occurring after contact with fine particles of coal.

Such processes include reusable hydrodynamic, shock-acoustic impact, etc., on the vessel surface, which, as is known, leads to the activation of the liquid matrix itself (to the possibility of the manifestation of synergistic [47] activation effects). This is explained by the fact that hydraulic shock activation of the liquid in combination with super active particles of coal (filler) can lead to the appearance of nonlinear effects in the functional properties of the final product, which its original elements (components) did not possess. In other words, the classical rule of "mixtures" may not hold, i.e., all necessary and sufficient conditions are created for the manifestation of synergy in the properties of the suspension activated according to the proposed method.

The constant search for optimal solutions that allow the fuel and energy complex of coal-producing countries to effectively master the necessary volumes of fuel transportation at the lowest possible cost of funds is currently one of the main, and most promising, tasks for the development and further stabilization of energy markets. Each type of transportation of solid fuel has its own specific features. To determine the areas of economically viable uses of a particular type of coal transport, it is necessary to take into account various factors, including the specific properties of the transported coal. When comparing the options for transporting coal by various modes of transport, the main indicators are: the technological properties of coal, (which includes Their physical and chemical characteristics, as well as including granulometric and ash composition, gas recovery, grindability coefficient, and tendency to grindability); the level of operating costs (the cost of transportation); capital investments; movement speed and delivery time; availability of transportation and throughput capabilities; maneuverability in ensuring transportation in various conditions; reliability and uninterrupted transportation, i.e., their regularity; and lastly, conditions for the efficient use of vehicles, mechanization, and automation of loading and unloading operations.

All of the above encourages researchers to develop a mathematical apparatus and also mathematical methods that would be close to cluster analysis, but would be based solely on the individual characteristics of coals and coal suspensions, taking into account the improvement in economic indicators.

The value of these indicators for each type of coal transport is different. It largely depends on the capacity and structure of the cargo flow from the deposit to the industrial site of the consumer, the distance of transportation, and a number of other factors, including the above-mentioned technological properties of coal.

One of the promising areas of transportation for solid bulk materials, which has recently been developed both in internal and external communications of industrial enterprises, is pipeline hydraulic transport.

It should be emphasized that the introduction of hydraulic transport can significantly improve technical and economic indicators; increase labor safety; reduce environmental pollution; industrial morbidity; ensure a wide range of automation of pipeline transport processes and the reliability of pipeline transport systems; and, ultimately, continuous non-overloading transport communication between supplier and consumer.

## 2. Application of Mathematical Models in CWS Combustion Processes

A mathematical model for the process of combustion of CWS in the form of suspension droplets is described in [34]. In this article, the static modes of the process are considered, and methods and a calculation scheme are proposed, which, therefore, made it possible to create a mathematical model and solve the optimization problem. The proposed methods are based on a thermodynamic description of the combustion process; further, the article calculates the heat and material balance. The solution of the optimization problem is performed for a dynamic mathematical model on the basis of the developed methods and an implemented calculation system. The combustion of droplets of a CWS was considered in a vortex furnace, and a physicochemical description of this process was given.

It is a well known fact, that climate change on our planet, specifically the impact of the greenhouse effect, is largely determined by the violation of the ozone layer from the combustion of fossil fuels. The combustion of this type of fuel is identified in modern research as one of the key factors causing climate change. The article [32] considers the properties of lignite coal and CWS using lignite coal. Based on the performed mathematical modeling, the article provides a calculation of the number of carbon dioxide molecules that arise as a result of the chemical reactions during the combustion process. In addition to this—and what is also important—is that the article provides a detailed review of publications made in recent years by scientists in the field of combustion of CWS using brown coal. Combustion studies, and their results, in this review are considered on the example of industrial recycling furnaces. This review presents the results of theoretical and experimental studies, taking into account the thermal properties of brown coal and the CWS that is based on it. The obtained results are compared with the results of numerical calculations performed using the ANSYS computer program. The comparison showed a high degree of convergence of the results. To build a mathematical model, new methods for approximating the step and generalized functions were developed. The developed approximation methods made it possible to increase the accuracy of approximations in the use of mathematical functions that describe the thermal properties of brown coal and CWS. The developed approximation methods do not have the same drawbacks that are typical for traditional expansions of step functions (when completed with the help and application of Fourier series). These methods are universal in nature and can be used for the purposes of mathematical modeling in describing various processes and systems in a wide range of scientific and technical problems. In article [32], the developed approximation methods were mostly used, for example, in order to determine the coefficients of kinematic viscosity, ash content, and the moisture content of brown coal and CWS. This made it possible to reduce the calculation error and obtain more accurate results using mathematical modeling. Additionally, in the article, numerical modeling of the combustion processes and fuel transportation by means of hydraulic transport were performed. The article presents the results of numerical simulation; further, it also describes the procedure by which the verification of the initial data and the result of the calculations are carried out. It is also shown that the convergence of data, and their location, in the selected uncertainty band corresponds to the conditions and criteria for verifying experimental data, which are accepted in the European and Eurasian Unions.

Typically, CWS has the following composition: 60–70% coal, 30–40% water, and 1% chemical additives; further, the development of this composition was carried out in the last 20 years. The composition was an alternative to fuel oil for combustion in industrial and municipal furnaces. A numerical study of the combustion process, the flow field of the process, and the features of heat transfer in an industrial furnace during CWS combustion, were all performed in the article [35]. The study was carried out using a computer program, Fluent, for describing the hydrodynamic processes. As shown by the results of the mathematical modeling, the combustion field in the furnace has a swirling form, in which high temperature gases—expanding outward—form recirculation areas directly in the burner zones. The effect of a drop in the combustion temperature with an increase in the length of the furnace is revealed, with the highest value of the combustion temperature being observed in the burner zone. The value of the swirl of the combustion field increases at the beginning of the transition from the front wall of the furnace to the rear, but then, subsequently, decreases. The article then notes that the type of distribution, in regard to the concentration of gases CO and $CO_2$, is mainly determined by the temperature field, namely—with an increase in temperature—the concentration of CO increases, and also the concentration of $O_2$ and $CO_2$ decreases. Moreover, the degree of loading for the boiler greatly affects the output average temperature, the maximum temperature of the furnace, and the rate of the combustion process.

The first developments that were made on the issue of the use and incineration of CWS appeared in the early 1980s. Currently, China is the largest manufacturer and user of CWS [37]. The currently, and widely, conducted studies [37] are aimed at improving dispersed fuels, their operational characteristics, and increasing the efficiency of the combustion process. In the course of research, a close correlation was established between the properties of CWS and characteristics such as the type and properties of coal raw materials. The established relationship leads to the need to take into account the purpose of the fuel in the production of CWS. For example, when burning CWS' "recycling" in pulverized boilers, conventional quality coal sludge can be used. While the solution of an important technological task is to increase the efficiency of power units, when faced with a reduced technical minimum there is a requirement for the use of higher quality, fine coal fractions that form the pulp.

Article [38] considers the mathematical model developed by the authors, which allows one to reproduce, with a high degree of accuracy, the experimental values of the integral characteristics of the CWS droplet combustion process. These characteristics include minimum temperatures and ignition delay times (as well as the coordinates for the start of the combustion front). The combustion of droplets containing petrochemical additives is considered in a hot oxidizer stream. The paper then describes the results of the numerical simulation carried out for the process of ignition of sludge droplets, which are common waste products that arise in coal processing. In the study for various sizes of droplets with a radius ranging from 0.25 mm to 1.5 mm, various values of the flow velocity of a high-temperature oxidizing gas from 0.5 m/s to 3 m/s, gas temperatures from 700 K to 1000 K, and the ignition delay time of drops were all determined. The selected values of the radius, velocity, and temperature of the droplets were determined, with consideration in taking into account the typical conditions of the combustion chambers. The results of the study showed a good agreement between the results of mathematical modeling and the data obtained experimentally. We used the Ansys Fluent software package, which is designed for numerical simulation of the CWS droplet ignition process, to analyze this data. It was found that the deviation of the results for the numerical simulation and the experimental data, on the characteristics of the inertia of the ignition process, does not exceed 5–10%.

In article [39], the authors describe the results of their theoretical and experimental research. The article shows studies of the ignition processes of CWS in the form of single drops. The surface of the droplets is covered with a thin water film. In the course of the study, the main parameters of the fuel combustion process were determined, such as the time for complete evaporation of the water droplet coating as well as the ignition delay, as depending on the ambient temperature. The errors in the calculated values, based on the mathematical models of the combustion process developed in the article, did not exceed 5%, relative to the experimental data. The mathematical models used in the study were built on the basis of a thorough analysis of the video recordings of the CWS ignition process. Mathematical models were developed taking into account the relationships within the complex of thermophysical and thermochemical processes. The article demonstrates a solution for a multifactorial nonlinear problem concerning the phenomenon of ignition of CWS particles. Approximate analytical solutions were obtained using asymptotic methods. The theoretical and experimental studies carried out have shown the importance of taking into account the thickness of the water film covering the surfaces of the fuel droplets. Additionally, film thickness has also been proven to be one of the main parameters for determining the conditions and characteristics of the CWS ignition process. The performed studies have shown that the characteristic evaporation time of the water surface film is from 45 to 60% for the entire induction period, depending on the film thickness.

CWS is a complex solid–liquid suspension. To study its properties, there have been a large number of research papers on the production and use of CWS. Technologies for using CWS are being developed around the world in various governmental, industrial, and academic institutions. The results of research in the field of production and application of CWS over the past 30 years are described in detail in article [36]. Particular attention, in the description, is given to various aspects of the CWS combustion process—for example, the structure and properties of coal, various additives used according to the technology conditions, and the possibility of using these additives for various types of coal are all described in detail. The article shows that the characteristics of the suspension capacity of coal, and the rheological properties of the CWS that are obtained on the basis of this coal, are largely determined by the particle size distribution. The article notes that, despite alternative sources of heat and electricity and the currently popular statement about the end of the coal era, modern efficient coal combustion technologies can help to reduce emissions of pollutants into the atmosphere. This fact speaks to the benefits of using coal as an energy source, at least until more adequate efficient and environmentally friendly alternatives are developed. In addition, the studies of the CWS combustion processes and the results of mathematical modeling obtained in these cases may be useful in the development of technologies for the use of other types of fuel. For example, we can then talk about biomass that is based on charcoal or trophy.

The new technologies for CWS incineration provide a range of good alternatives for the incineration process. These alternative possibilities fully meet modern requirements for environmental protection. Therefore, the issues of using coal suspension as an energy source undoubtedly require the most thorough of studies and further research. Study [40] can be cited as an example. This paper presents the results of a comprehensive study of continuous and cyclic CWS combustion processes. The advantages of cyclic combustion are determined by the nature of the movement of bulk coal material in the cyclic flow circuit of the fluidized bed; further, the circuit is formed by a combustion chamber, a cyclone device, and a furnace riser. As shown by the results of experimental studies, the cyclical nature of the change in the oxygen concentration for fuel combustion contributes to significant changes in the combustion mechanisms and the kinetics of the combustion process. The article developed a mathematical model for the cyclic process of fuel combustion. The initial concept of this mathematical model takes into account the cyclical nature of the change in the oxygen concentration for fuel combustion. The mathematical model helps to make predictions about the change in temperature of the inner surface of the combustion chamber and its central part. Additionally, with the help of a mathematical model, the mass loss of fuel is determined during the cyclic nature of combustion in a fluidized bed when in air.

Studies have shown that CWS is an attractive low-cost alternative fuel. The advantage of this technology is also a high degree of reliability in the transport and preparation of fuel for use. The gasification efficiency of coal–water suspension is determined by its high carbon content and low viscosity. These characteristics allow you to increase the heating rate. The CWS' fine atomization plays an important role in this. Article [47] considers the rheology of a coal–water suspension with a coal content of 30 to 60%. Moreover, power law models, specifically Casson and Herschel Buckley models, were used to study the rheology of CWS; the models also showed the pseudo-plastic behavior of the CWS. Further, the preparation of CWS was carried out using polyvinyl alcohol (PVA) and triethanolamine (TEA).

For several decades, the efforts of researchers have been directed to find a practical solution to the problem of transporting CWS through a slurry pipeline. Solving this problem requires understanding and a modeling of the complex phenomena involved. A significant increase in the computing power of computer systems and the widespread use of application software packages for computational fluid dynamics, have made it possible to collect large amounts of information at the local level regarding the flows of the suspension that is transported through the slurry pipelines. This is the main difference between modern CWS research methods and traditional approaches using simplified methods of mathematical modeling with a macroscopic description of processes. An example of this is in review article [48]. This article explores the potential of computational fluid dynamics for modeling flows in slurry pipelines. A detailed description of modern modeling methods is carried out, with a review of important publications on this topic. The main attention in the article is focused on the assessment of the potential of various methods of computational fluid dynamics. The issues of interaction between computational hydrodynamic modeling and experimental studies are considered. In addition, the main causes that create uncertainties in CFD models are considered. The article evaluates existing models in terms of their interpretive and predictive ability.

There are articles [49,50] that consider mathematical models that which make it possible to determine the optimal conditions for the ignition of promising CWS. At the same time, the criteria for optimizing the ignition of CWS, which include petrochemicals, are the minimum possible ambient temperatures and a short ignition delay time. Three optimal regimes have been experimentally determined under which physicochemical transformations effectively occur when CWS is heated. The first mode is characterized by intensive thermal decomposition of the coal component after the evaporation of the liquid components of the fuel. The second mode is characterized by gasification of the coal component; this mode occurs under conditions that result in boiling liquid components. Then, there is a heterogeneous combustion of the solid residue. In the third mode, the gas mixture is ignited. Ignition begins directly in the vicinity of fuel particles and passes into a heterogeneous combustion of the solid residue. For the identified regimes of physicochemical transformations, the ambient temperature ranges, and other conditions for their occurrence, are established.

On the basis of the experimental data obtained and the results of their statistical processing, a mathematical model of physicochemical transformations under the heating conditions of CWS with different compositions of components was proposed. The developed model makes it possible to make predictions about the course of the combustion process. The model is built taking into account functional relationships in physical and chemical processes. The model describes inert heating, evaporation, thermal decomposition, and exothermic reaction during combustion. The obtained results of theoretical studies carried out on the basis of the proposed model helped to determine the degree of influence of the parameters on the constituent parts of the fuel, such as the heating conditions that were found to be effective modes of physicochemical transformations.

## 3. Summary

### *3.1. Mathematical Models on the Combustion of Water–Coal Fuel*

The combustion of water–coal suspensions is a heterogeneous process of chemical interaction of solid fuel with an oxidizer, and is complicated by parallel steam generation in the suspension, which significantly changes the reaction characteristics of the fuel and the conditions of heat and mass transfer both on the surface and in its volume. This leads to an intensification of the total burnout rate and high thermal stresses of the process [51].

The chain nature of the processes of oxidation and combustion of coal to a certain extent predetermines the decisive role of water and steam. The main total (final) reactions of combustion of water–coal suspensions in a gaseous oxidizer (air), are the reactions of oxidation and combustion of coal with oxygen and water vapor, as well as secondary reactions of carbon dioxide reduction, conversion of carbon monoxide, methane formation, etc. A feature of these reactions during the combustion of water–coal suspensions is their flow at a high concentration of water vapor and temperatures close to the theoretical temperatures found in the combustion of carbon.

An analysis, carried out in [52], of the reactions of oxidation and combustion of coal particles in the presence of water and water vapor, shows that moisture can intensify reactions with carbon, both through free hydroxyl radicals and also through the mechanical transfer of other oxidants dissolved in water to the coal surface. Low temperature coal oxidation reactions in the presence of water proceed with a very low activation energy. In washing out carbon dioxide, methane, and nitrogen from the coal pores and from the surface, water significantly increases the sorption capacity of coal with respect to oxygen and increases the rate of desorption of reaction products, thereby improving mass transfer on the coal surface.

It has been experimentally established that during surface combustion of a layer of a mixture of small particles of coal with water (as a result of humidity and temperature gradients), there is a continuous transport of moisture from the inner layers of the fuel to the burning surface. This, however, is complicated by the processes of evaporation of the moisture and gas formation, which is as a result of the interaction of moisture and carbon of the fuel as it warms up. The combustion process of such a mixture is accompanied by the formation of a narrow water vapor superheat zone, which is located directly behind the surface combustion zone and characterized by high thermal resistance and large gradients of temperature and water vapor concentration.

According to [52], the distinguishing features found in the ignition and combustion of a coal–water suspension drop are high concentrations of water vapor near the reaction surface; relatively large sizes of suspension droplets that react with atmospheric oxygen when compared with coal dust; and, as a consequence, the determining role of mass and heat transfer not only during the combustion of the drop, but also to a large extent during its ignition.

Immediately after the drop enters the combustion chamber, evaporation begins from its surface, which occurs at a constant temperature as per the drop and a decrease in the temperature of the medium (due to heat consumption for evaporation). Visible changes in color, volume, and the shape of the drop are absent. As the temperature rises on the surface of the droplet, the second stage begins—during which further heating of the droplet, overheating of water vapor, and interaction of the fuel with water vapor, continue. The temperature of the medium is then equalized. The drop begins to increase in volume. The reaction of fuel carbon with water and water vapor is endothermic, therefore temperatures rise. The minimum temperature of the environment at which ignition of the drops of coal–water (composed of coals of different grades) suspensions arise is different. However, it must be noted, that for all coal–water suspensions the minimum temperature is much lower than for dry coals of the same grades. Increase in droplet size is a consequence of the intense vaporization and thermal decomposition of the coal inside the droplet. An increase in the volume of the drop leads to an increase in the porosity of the dried layers, which reduces heat transfer to the central region of the drop and also reduces the rate of moisture evaporation and thermal decomposition of coal particles. The third stage begins with ignition from a drop of combustible gases, with a further increase in both the ambient temperature and the drop itself. The drop becomes lighter and, in some cases, larger in volume. Afterburning of the coke residue is the fourth (last) stage of the process. It is not much different from the burnout of a particle of dry coal, however, the burnout rate of a drop due to the highly developed specific combustion surface is greater than during the combustion of a particle of dry coal. In [53], a mathematical model was constructed on this topic.

Thus, the combustion of a drop of suspension is considered as a heterogeneous process that proceeds with a continuously changing volume and therefore composition of the fuel. This is further complicated by the process of volumetric afterburning of combustible gases, which is continuously generated from the central part of the drop.

Study [54] presents a model for the process of atomization and the combustion of suspension coal fuel. The combustion efficiency of this fuel significantly depends on the quality of its atomization [54].

The stability and completeness of fuel burnout in the combustion chamber are determined by the degree of atomization of the fuel that is introduced into the chamber and also the perfection of the aerodynamics of gas flows inside the chamber. These qualities provide reliable conditions for flame ignition and stabilization; reliable mixing of the fuel with the oxidizer and temperature distribution; as well as optimal conditions for fuel burnout throughout the entire volume of the chamber. The atomization quality of a coal–water suspension in the combustion chamber depends on the perfection of the design of the atomizer and the properties of the fuel.

It is known that the combustion of coal–water fuel differs significantly from a similar process when using pulverized coal [54]. At the same time, it is argued that the influence of the brand of coal, and its ash content on the ignition temperature and combustion stability is insignificant. However, the results of bench tests and operating experience show that when burning batches of CWF, which is prepared from highly metamorphosed coals and anthracites, a higher initial heating of the furnace space is required in order to initiate the process of fuel ignition and its further stable combustion. A similar phenomenon was also recorded when using coal–water fuel prepared from high-ash coal sludge. All of this indicates that the mechanism of spraying and the mathematical model of ignition and combustion of coal–water fuel require adjustment.

Considering the polydispersity of coal particles in CWF during spraying, pure coal particles ("drop-particles" larger than 80–100 μm) are formed, from which a liquid film with the finest particles breaks off due to hydrodynamic friction forces, and coal–water drops, consisting of thin particles of coal and liquid phase, are thus developed. Therefore, the mechanisms of ignition and combustion of a polydisperse flow of CWF droplets must be considered when taking into account the laws of heat and mass transfer, as well as chemical reactions that occur in liquid coal drops and ordinary coal particles [55].

Thus, it is assumed that the combustion process of sprayed CWF droplets is a combination of combustion of two model systems: coal particles with a diameter of more than 80–100 μm and coal–water droplets with a diameter in the range of 80–100 μm. This physical model of CWF spraying was confirmed by mathematical calculations and experimental results [55].

The experimental tests carried out showed that CWF, when prepared from coals of various grades and ash content, reliably ignite and burn effectively in a swirl furnace. The mechanical under burning of the fuel (the content of combustibles in the trapped ash particles) is no more than 3–5%. A similar indicator for layered coal furnaces is 20–60%.

The ignition temperature and the time to reach a stable regime of independent combustion of various types of CWF depend on the brand of coal and its ash content, the content of which are harmful emissions that are 3.3–4.3 times lower than the maximum allowable concentrations (for enterprises that operate in Kyrgyzstan and Russia).

The economic efficiency in the use of coal–water fuel was obtained due to the different cost of the fuel components when using CWF and when using ordinary coal in boiler houses. Moreover, payback of capital costs takes no longer than 2.5 years.

Thus, the implementation of this technology for the purposes of the combustion of coal–water fuel in swirl furnaces of small and medium-sized boilers makes it possible to obtain a significant economic effect and reduce harmful emissions in the environment.

### *3.2. Mathematical Models of Transportation of Coal–Water Suspensions*

According to Offengenden [50], a study conducted 40 years ago, the most efficient application and use of hydraulic transport can be under the following conditions:

- when it is indispensable for any other modes of transport due to the tendency for the spontaneous combustion or due to the high water content of the fuel;
- when, due to the conditions of the terrain, it is possible to reduce the length of the pipeline transport main when compared to rail or to other modes of transport; further, while hydraulic transport is especially favorable in mountainous or rough terrain there is still an excess of geodetic height that the supplier must contend with when compared with the consumer;
- when the fuel production areas are remote from the places of its consumption, and when there is an absence, or weak development, of highways and railways;
- in the absence of large reserves of labor in the pipeline transport, as in they do not exceed 30–40% of the cost of rail and road transport.

The last few decades have been characterized by a noticeable expansion globally in the scale of pumping various kinds of hydraulic mixtures via pipeline transport.

Design studies are underway for a number of pipeline transport systems in the BRICS countries as well. The most striking recent work in this area is found in article [56] by the authors D. Das and S. Das. See also [57] by Wang, Zhao, Zhang, and Hu [58] as well as by Yi and Zhou. Features of transport are found, first of all, in the variety in properties of bulk materials, which in turn have a decisive influence on the properties and characteristics of slurry and the parameters of pressure pipeline transportation. This was studied in the United States and Europe before their attempts to completely switch to "green" energy. Articles [59–61] show the latest research at that time for these countries. However, it should be noted that strong attention to this topic has been attracted in China. In [60,62], the properties of suspensions and surfactants are studied. These properties should be used in the future when constructing mathematical models for the motion of suspensions and individual particles.

From the current practice of preparing, transporting, and burning artificially watered solid fuels, it is possible to divide these into classes of low- and high-reactivity mixtures [63,64].

This division depends on the heat value of the original coal and the moisture content of its slurry. The economy of the second option is due to the cost of construction and operation of devices for preliminary dehydration. To take into account the specific technical capabilities of the existing boiler and furnace equipment when switching to the combustion of CWS, comprehensive studies were thus carried out in order to select the combustion technology for the Karakechi brown coal when delivered to the consumer by pipeline transport. At the same time, the following research tasks are defined:

- analysis of the combustion features of artificially watered Karakechi brown coal in a wide range of moisture content and size, this being of the initial coal particles that are based on bench studies of the combustion process in a single flame;
- determination of the conditions for stable combustion of flooded Karakeche brown coal in industrial furnaces of boiler units, taking into account the above analysis;
- analysis of the effectiveness and selection of industrial schemes for burning Karakechi brown coal based on the studies;
- selection of the optimal storage technology, intraschool transport, and supply of high-moisture Karakechi brown coal to the furnace, taking into account the studied combustion schemes.

The technique for studying the process of combustion of CWS of Karakechi brown coal is based on the study of the process in separate characteristic zones along its course.

Previously, studies of the combustion of CWS were carried out by individual authors.

In [65] Wan, Yu, Wang, and Sun, the authors who studied pyrolysis processes and suspensions, CWS were used as fuel. In [66] Li, Liu, Wang, and Cheng carried out a fairly extensive study of mixtures and suspensions. Additionally, in [67] Yao, Zhao, Chen, and Liu studied the ratio of water and coal when in suspension and the effect of their concentrations on qualitative characteristics.

A feature of the experimental studies was that the possibilities of controlling the moisture content of the supplied fuel were limited by the fluidity of the CWS at $W^{daf} \leq 43 \ldots 45\%$ [26,68]. With a further increase in humidity, starting from ~46%, the mixture becomes fluid with a characteristic manifestation of viscoelastic properties inherent in non-Newtonian liquids. Atomization of such a mixture by a nozzle located in the upper cover of the combustion chamber leads to the formation of droplets, including coal particles and water.

Sampling from the combustion chamber showed that the thermal effect on the droplets of the CWS leads to the agglomeration of the initial dust particles that make up the droplet. The nature of the distribution of crushed samples of agglomerates, in terms of size, is close to the distribution of particles of the initial dust. A visual study of fuel samples of the agglomerates shows that the presence of lighter-burnt small inclusions and also the presence of large particles with obvious signs of under burning. The analysis of crushed agglomerate screenings for the content of combustible components also confirms the staging of the fuel particles burnout of the agglomerate.

In order to select effective technological schemes for the purposes of burning Karakechi brown coal that is delivered to TPPs via pipeline transport, the pipelines were modeled by utilizing the equipment of a pilot plant on a TP-35 boiler, as well as using the moisture content and fractional composition of the initial coal dust. At the same time, within the initial stages of the research, the task was set: to formulate the modeling conditions when considering the effect of the two ways that water can be introduced into the furnace. That is to say, either through nozzles that are installed through a CWS or instead through the main burners of the boiler (together with ordinary coal dust through the same nozzles and burners) while maintaining the analogy of the physical chemical characteristics of the fuel dry mass and the proportion of the water. Similar studies were also carried out by researchers from Turkey in [69] and by the authors Dinçer, Boylu, Sirkeci, and

Ateşok [70–72]. Such an approach to modeling processes on a full-scale boiler is convenient in that the conditions of geometric, kinematic, and dynamic similarity, which are all generally accepted in aerothermodynamics, are satisfied in advance. Thus, we are talking about the selection of only additional conditions that implement thermal similarity, which, due to the inadequacy of the distribution of dust and sprayed droplets in the reagent flows, will be approximate. Industrial experiments carried out on the TP-35 boiler with a steam output of 4.88 kg/s showed the fundamental possibility of thermal modeling [73].

The authors of the article themselves studied the properties of Karakechi coal, its mixture with water [63,64], and also used data on coals and mixtures previously studied by other authors [69,74]. In paper [68], as well as studies [32,33], experimental and analytical data were obtained. Below, we present the main results of research, including those obtained using mathematical modeling methods. Processing of the results was carried out as per the area of active combustion, from the nozzle exit to the zone with the maximum temperature, as well as the location that varied depending on the moisture content in the sprayed CWS and the temperature of the chamber wall. For example, at humidity $W^{daf}$ = 48% and wall temperature $T_w$ = 1470 K, the length of this section is $l_f$ = 0.5 m, and at $W^{daf}$ = 55% the same wall temperature is $l_{daf}$ = 1.0 m. Within the $l_f$ section, a shorter section $l_{ign}$ can be distinguished from the nozzle exit to the beginning of the flame glow. The length of this section, as a rule, was $l_{ign} = 0.2\ l_f$. According to the values of $l_{ign}$ and the flow rate of the reagents, the total time for heating the coke residue before the start of its active burnout was determined, and the values of $l_{comb} = l_f - l_{ign}$, were used to determine the burnout time of the coke residue. These results formed the basis of the methodology for assessing the influence of the moisture content of the CWS on the conditions for the combustion to proceed.

Additionally, it was interesting to note, that, from the point of view of the initial data, the mathematical models were obtained in the scientific work [74]. Here, the properties of coals were studied, and the combustion constants of coal dust were determined. When determining the combustion constants $k_{ign}$ in the initial section and then determining $k_{comb}$ in the section where agglomerated particles underwent active burnout and which entered into a chemical interaction with oxygen in the flame sections $l_{ign}$ and $l_{comb}$, the equations of the dynamics of combustion of coal particles proposed by Babiy and collaborators [74] were demonstrated. Estimation of the experimental coefficients $k_{ign}$ and $k_{comb}$ in the presence of experimental data on the average wall temperature $T_{mid}$, K; the density of CWS $\rho_{mix}$, g/m$^3$; coke residue density $\rho_{coke}$, g/m$^3$; and the oxygen concentration $O_2$ was carried out according to the equations of connection between the degree of burnout of a polydisperse torch and the heat release of volatile and coke particles.

In the process of calculations, mathematical methods of data processing were used. As a result of solving the coupling equations, mathematical dependencies were obtained:

$$k_{ign} = k_{ign}{}^{\circ} \cdot (1 - W^{daf}) \cdot \rho_{coke} / \rho_{mix}. \tag{1}$$

$$k_{comb} = k_{comb}{}^{\circ} \cdot (1 - W^{daf}). \tag{2}$$

where $\rho_{coke}$ is the density of the coal component of the mixture, kg/m$^3$; $k_{ign}{}^{\circ} = k_{comb}{}^{\circ} = 1.23$.

Significant progress in the experimental study of the properties of coal dust and processing of the results was obtained for Kazakh and Kyrgyz coals. Comparing the values of these coefficients with similar indicators in the dust of the Karakechi brown coal that are obtained in [74], one can note the discrepancy between the results by almost a factor of two: $k_{ign} = k_{comb}$ = 0.55–0.74 for the CWS, while for the dust of the same coal $k_{ign} = k_{comb}$ = 1.34. The latter is obviously due to the lower relative content of combustible components in droplets with sizes equivalent to similar coal particles. To assess the conditions for the stable combustion of the coal–water mixture of Karakechi brown coal, the balance heat equations were compiled for the $l_{ign}$ and $l_{comb}$ sections. This made it possible to determine the reduced heat release of volatiles, which, in the first approximation, can be taken as a criterion for the stability of combustion of high-moisture coals $Q_{volatile}{}^{h.h.c}$ (kJ/(kg of percent of humidity)):

$$Q_{volatile}{}^{h.h.c} = [Q_{volatile} \cdot (V^{daf} - V^{daf}{}_{ign}) - Q_W - Q_A - Q_{reag}]/W^{daf}. \quad (3)$$

where $Q_w = 2500 \cdot W^{daf} + C_{pw} \cdot \Delta t \cdot W^{daf}$ is the amount of heat for evaporation and heating of fuel water, kJ/kg; $Q_A = C_{pA} \cdot \Delta t' \cdot A^{dry}$ is the amount of heat for heating the ash part of the fuel, kJ/kg; $Q_p = \Delta t' \cdot [V^{daf} \cdot C_{pv} + (1 - V^{daf})\, C_{pcoke} + \alpha V^{\circ} \cdot C_{pair}]$ is the amount of heat for heating reagents, kJ/kg; $C_{pw}$ is the average heat capacity of steam in the temperature range $\Delta t' = t_{mid} - t_o$, kJ/kg K; $C_{pA}$ is the average heat capacity of ash in the temperature range $\Delta t' = t_{mid} - t_o$, kJ/kg K; $C_{pv}$ and $C_{pcoke}$ are the average heat capacities of volatiles and coke in the temperature range $\Delta t' = t_{mid} - t_o$, kJ/kg K; $C_{pair}$ is the average heat capacity of air in the temperature range $\Delta t' = t_{mid} - t_o$, kJ/$m^3$ kg K; $\alpha$ is the coefficient of excess air in the burner; and $V^o$ is theoretical air volume, $m^3$/kg.

In addition, the researchers in article [74] compared the data for coals with similar properties. Further, these data were also included in the mathematical models. For the CWS of Karakechi brown coal with $W^{daf}$ = 48%, the value of $Q_{volatile}{}^{h.h.c}$ is ~80 kJ/kg % moisture; for Bashkir coal with $W^{daf}$ = 56% $Q_{volatile}{}^{h.h.c}$ = 91 kJ/kg % moisture; and for Chikhez coal with $W^p$ = 43.5% $Q_{volatile}{}^{h.h.c}$ = 144 kJ/kg % moisture. At the same time, Chikhezian coal burns steadily in flare furnaces, while direct combustion of the coal–water mixture of Bashkir coal without illumination by an additional source of heat release is difficult to organize under these same conditions.

The temperature value that ensures stable combustion of the coal–water mixture of Karakechi brown coal depends on the humidity of the mixture at constant values of the degree of heat supply (removal) by the walls, the fractional composition of the initial dust, and the size distribution of sprayed droplets, in the range $W^{daf}$ = 48 . . . 55%, $T_{min}$ = 1130 . . . 1150 K. Temperature data are essential for boundary conditions in combustion reactions.

The results of studies performed on a pilot plant for the preparation and combustion of Karakechi brown coal, that was created in relation to the boiler TP-35 [63,64], in general, confirmed the nature of temperature changes, burnout of volatiles and coke residue, as well as the general dependence of the process on the degree ballasting with moisture and fractional composition of the initial fuel. At the same time, dust combustion is characterized by a shorter section lf from the burner cutoff to the zone of maximum temperatures $T_f$, which are a higher level of temperatures themselves and therefore the degree of burnout. When switching to combustion of a coal–water mixture, combustion was delayed, the length $l_f$ increased by 5–6 times, and the degree of burnup at this level decreased to $a$ = 0.65 . . . 0.75. The degree of burnout of the coal–water slurry in the outlet window of the combustion chamber was $a$ = 0.82 . . . 0.85. The average temperature level in the furnace was in the range of 1340...1350 K. The maximum size of agglomerates formed in the process of spraying the coal–water slurry in the furnace was 1000...1200 µm with an average value of 350...400 µm. These data later formed the basis of the coal particle model.

The calculation of the degree of fuel burnup for these conditions with a previously determined coefficient $k_{ign}$ = 0.67 showed an insignificant discrepancy with its experimentally determined value (~8 . . . 12%). Verification of the same method of calculation for dry dust of Karakechi brown coal at $k_{comb}$ = 1.34 gave a discrepancy, when compared with the experiment, of 5...7%. At the same time, the distributions of dimensionless temperatures and the degree of burnup revealed under the conditions of the stand [64] are typical for the combustion of dust and CWS in the TP-35 boiler. Despite the lower values of the kinetic constants $k_{comb}$ for agglomerates when compared to dust, the burnout time of CWSs increases significantly due to a decrease in the flame temperature and an increase in the size of agglomerates compared to the size of dust particles. The obtained values of the combustion constants were included in the standard methods that are used for calculating coals for the Kyrgyz Republic.

Next, we will consider a mathematical model for constructing a pipeline for a coal–water mixture and compare the calculations for this model with data for transportation by road.

The total costs $K_{c.p}$ for the construction of pipeline transport facilities with a direct-flow water supply system are determined by the formula:

$$K_{c.p} = K_{p.c} + K_z + K_p \cdot L_p + \Sigma K_{a.b} + K_c, \quad (4)$$

where $K_{p.c}$ is the cost of construction of the pulp preparation complex, USD;

$K_z$—cost of sump construction, in USD;
$K_p$—cost of construction of 1 km of the pipeline, in USD;
$K_{a.b}$—cost of construction of artificial structures along the pipeline route, in USD;
$K_c$—cost of construction of the CWS storage facility, in USD;
$L_p$—pipeline length, km.

Formula (4) contains all practically significant capital costs. At the same time, the current costs of operating the pipeline are significant.

Annual operating costs for the maintenance of all hydraulic transport devices are determined by the formula:

$$E_{c.p} = E_{indep} + E_{dep}, \quad (5)$$

where $E_{indep}$ and $E_{dep}$ are expenses that do not depend on and that which do depend on the operating time of pipeline transport for a year, respectively, in USD 1000.

The norms of expenses for the maintenance of pipeline transport devices are determined for enterprises located in the central regions of the country. The cost of electricity is taken at the tariff—USD 40 per 1 kVA of installed capacity and USD 0.2 per 10 kWh of power consumption.

Annual costs that do not depend on the operating time of the pipeline transport (with direct-flow water supply) are determined by the formula:

$$E_{indep} = E_{p.c} + E_z + E_{p.st} + E_p \cdot L_p + \Sigma\, E_{a.b} + E_{pp}, \quad (6)$$

where:

$E_{p.c}$, $E_z$, and $E_{p.st}$ are the cost rates, independent of time, for the maintenance of the pulp preparation complex, of the sump; main; and auxiliary pumping stations, respectively, per year, in USD 1000;
$E_p$ is the norm of the expenses for the maintenance of 1 km of pipelines per year, in USD 1000;
$E_{a.b}$ is the expenses for the maintenance of artificial structures along the pipeline route for the year, in USD 1000;
$E_{pp}$ is the rate of expenses for the maintenance of the slurry storage facility at the State District Power Plant, in USD 1000;
$L_p$ is the pipeline length, in km.

Annual costs, independent of the operation of pipeline transport time (and when taking into account the norm), make up: $E_{indep} = 1604$, in USD 1000.

Annual costs in USD 1000, depending on the operating time of the pipeline transport system, are determined by the formula:

$$E_{dep} = 0.001 \cdot p \cdot T \cdot (E_{dep.p.c} + E_{dep.z} + E_{dep.p.st}), \quad (7)$$

where:

p is the number of hydraulic transport shifts per day;
T is the number of pipeline transport operation days per year;

$E_{dep.p.c}$, $E_{dep.z}$, and $E_{dep.p.st}$ are the cost rates, depending on the operating time, for the maintenance of the complex slurry pumping station; sump and auxiliary slurry pumping station; and head slurry pumping station per shift, respectively, in USD 1000.

Thus, the model takes into account all significant operating costs.

The reduced costs for the Kara-Keche–WPP pipeline transport system were determined by the formula:

$$P_{c.p} = E_{c.p} + Q_{standart} \cdot K_{c.p}. \quad (8)$$

For the fuel and energy complex as a whole, the normative efficiency factor $Q_{standart}$ is set at the level of 0.12 by the standard methodology. From here: $P_{c.p}$ = 3232.866 in USD 1000.

We present the results of the calculation according to the developed model and obtain the results per 1 ton of the transported coal–water mixture.

The cost of a pressurized hydraulic transportation of Karakechi brown coal from the Kara-Keche deposit to the industrial site of the TPP will be:

$$Pr_{c.p} = E_{c.p}/N, \quad (9)$$

$$Pr_{c.p} = 0.7098 \text{ USD/ton},$$

where N is the productivity of the pipeline transport system, in tons/year, and equal to 3 million tons/year.

Thus, the value of USD 0.7098/ton should be compared with the same parameter for road construction and vehicle transportation.

Capital investments for the construction of road transport facilities and the acquisition of a rolling stock fleet are determined by the formula:

$$K_{a.t} = K_{eq} + K_{r.s}, \quad (10)$$

where:

$K_{eq}$—the cost of construction of permanent structures and devices, in USD 1000;
$K_{r.s}$—the cost of acquiring rolling stock, in USD 1000.

Next, we reveal the meaning of expression (11).

The total costs for the construction of permanent (without cargo and storage) vehicles in transport hubs are found by the formula:

$$K_{eq} = K_{road} \cdot L_{road} + K_{br} \cdot L_{br} + K_{s.p} \cdot F_{s.p} + K_{gar}, \quad (11)$$

where:

$K_{road}$—the cost of building 1 km of road, in USD 1000;
$K_{br}$—cost of 1 m of bridge length, in USD 1000;
$K_{s.p}$—the cost of 1 thousand $m^2$ of coverage of areas near loading and unloading devices, in USD 1000;
$K_{s.p}$—the cost of building a garage, in USD 1000;
$L_{road}$—length of the highway, in km;
$L_{br}$—bridge length, in m;
$F_{s.p}$—coverage area, in 1000 $m^2$.

Capital investments for the purchase of rolling stock are determined by the formula:

$$K_{r.s} = \varphi \cdot \Sigma(K_a \cdot N_a \cdot t/T), \quad (12)$$

where:

$\varphi$ is a coefficient that takes into account the number of cars under repair, stock, etc.;
$K_a$—the cost of a car of a certain type, in USD 1000;
$N_a \cdot t$ is the number of hours of use per day for a car engaged in transportation;

T—the average duration of car use per day, in h.

As a transport unit, a dump truck with a carrying capacity of m (per 10 tons) is used.

To ensure the cargo flow of S (per 3 million tons) of coal per year with 1.5 shifts of a car for u (per 200 working days) at a distance of 60 km, one car must make n (per 2 trips per day). From here:

$$N_a = S/(n \cdot u \cdot m), \quad (13)$$

$$N_a = 3{,}000{,}000/(2 \cdot 200 \cdot 10) = 750 \text{ autos},$$

at $\varphi = 0.2$; $K_a = 16.0$ USD 1000; and T = 12 h.

Capital investments for the purchase of rolling stock are $K_{r.s} = 2339.61$ in USD 1000.

Thus, calculations according to Formula (10) take into account all significant capital costs.

The indicators of the cost of roads are determined depending on the annual gross freight turnover in gross million tons. Estimated gross freight turnover is determined by the formula:

$$Q_{gross} = \Sigma\, Q_{cargo} \cdot \eta, \quad (14)$$

where

$Q_{cargo}$ is the freight turnover handled by the rolling stock of a certain type, mln.t. per year;
η—transition coefficient from net freight turnover to gross freight turnover, determined for a given type of rolling stock;
η—for a dump truck with $\beta \cdot \gamma = 0.5$ is equal to $\eta = 3.4$,
β is the mileage utilization factor;
γ is the utilization factor of the vehicle's carrying capacity.

From here: $Q_{gross} = 10.2$ million gross tons.

Next, current operating costs are considered.

The total operating costs for road transport for the year is determined by the formula:

$$E_{a.t} = E_{r.s} + E_{eq}, \quad (15)$$

where:

$E_{r.s}$—expenses depending on the amount of work (for rolling stock) for the year, in USD 1000;
$E_{eq}$ is the cost of maintaining permanent devices for the year, in USD 1000.

Annual operating costs in USD 1000, depending on the volume of work in the transport hub, are generally determined by the formula:

$$E_{r.s} = 0.365\,(0.1\Sigma E_{load} \cdot N_{load} \cdot L + 0.1\Sigma E_{emp} \cdot N_{emp} \cdot L + \Sigma E_{stan.h} \cdot N_{auto} \cdot T), \quad (16)$$

where:

$E_{load}$ and $E_{emp}$ are the rates of expenses per 10 vehicle km, loaded and empty mileage of certain types of vehicles, in USD;
$E_{stan.h}$ is the rate of expenses for one hour of idle time on the line of cars of certain types, USD;
$N_{load} \cdot L$ and $N_{emp} \cdot L$ are the average daily mileage of cars of certain types in loaded and empty condition, in vehicle km;
$N_{auto} \cdot T$—average daily downtime of cars of the corresponding types on the line, car h.

For dump truck:

$E_{load} = 4.20$ USD $N_{load} \cdot L = 45{,}000$ vehicle km

$E_{emp} = 3.41$ USD $N_{emp} \cdot L = 45{,}000$ vehicle km

$E_{stan.h} = 2.38$ USD $N_{auto} \cdot T = 750$ vehicle km

From here: $E_{r.s} = 13{,}118.56$ in USD 1000.

Annual operating costs in USD 1000 (for the maintenance of permanent devices), are determined by the formula:

$$E_{eq} = \Sigma E_{road} \cdot L_{road} + 0.001 \Sigma E_{br} \cdot L_{br} + 0.001\, \Sigma E_{s.t} \cdot F_{s.t} + E_{gar}, \quad (17)$$

where:

$E_{road}$ is the rate of expenses for the maintenance of 1 km of a certain category of road per year, in USD 1000;
$E_{br}$ is the rate of expenses for the maintenance of 1 m of the bridge length per year, in USD 1000;
$E_{s.t}$ is the rate of expenses for the maintenance of 1000 $m^2$ of sites near loading and unloading devices per year, in USD 1000;
$E_{gar}$ is the rate of expenses for the maintenance of the garage for the year, in USD 1000;
$L_{road}$ is the road length, in km;
$L_{br}$ is the bridge length, in m;
$F_{s.t}$ is the coverage area of the sites, in 1000 $m^2$.

For road transport of Karakechi coal with a cargo flow of 3 million tons per year:

$E_{road}$ = 8.19 USD 1000;
$E_{br}$ = 109.2 USD;
$E_{s.t}$ = 837.2 USD;
$E_{gar}$ = 2548.0 USD 1000.

From here: $E_{eq}$ = 3053.2 USD 1000.

Total annual operating costs for road transport: $E_{a.t}$ = 16,171.80 USD 1000.

The reduced costs for road transport of coal to TPPs will be:

$$P_{a.t} = E_{a.t} + Q_{standart} \cdot K_{a.t}, \quad (18)$$

$$P_{a.t} = 19{,}102.36 \text{ USD } 1000.$$

The cost of transporting coal by road:

$$Pr_{a.t} = E_{a.t}/N, \quad (19)$$

where N is the productivity of the motor transport system, in tons/year, equal to 3 million tons/year.

$$Pr_{a.t} = 5.39 \text{ USD/ton}.$$

Thus, we obtained that the value of 5.39 USD/ton is significantly higher than the analogous parameter during pipeline transportation.

The economic effect from the use of hydraulic transportation of Karakechi brown coal in comparison with road transport, when determined by the difference in the reduced costs, will be:

$$E_{c.p} = P_{a.t} - P_{c.p} = 17{,}689.49 \text{ USD } 1000/\text{year}.$$

An analysis of the technical and economic indicators of the studied technological schemes showed the prospects for using the scheme for burning pipeline transported Karekechi brown coal in boilers equipped with a dust system with fan mills and dust concentrators.

### 3.3. Mathematical Modeling—Artificial Neural Network Approach

Recently, a fairly large number of publications have appeared in which mathematical models are developed to describe the processes associated with coal–water suspensions based on artificial neural networks. For example, we can note article [75]. In this article, the authors describe a mathematical model they developed that allows for the predicting of CWS viscosity value, depending on the system parameters, by using an artificial neural network. The article presents the results of experimental studies for high-ash Indian coal. The Levenberg–Marquardt algorithm was applied to train the artificial neural network;

the multiple correlation coefficient was 0.99. The high value of the correlation coefficient indicates the reliability and adequacy of the developed neural network model.

Additionally, the works of [76–78] can also be mentioned. Vaferi, Samimi, Pakgohar, and Mowla considered the option of constructing an artificial neural network in order to predict the thermal state of a mixture [76]. Chin, Lai, Ibrahim, Jaafar, and El-Shafie built a model that predicts the mixture velocity [77]. Further, Dumitriu T., Dumitriu R., and Manta developed models of gel behavior [78].

The articles of [79,80] present the results of experimental studies of the combustion of pulverized coal. The results obtained are then used to train the neural network. In the articles, the authors solve the problem of burning coal–water suspensions with the help of a new efficient and environmentally friendly technology. The developed technology is based on the use of mathematical models and methods of artificial neural network theory. The technology helps to prevent the occurrence of emergencies during the combustion of fuel in boiler plants. The proposed automated control systems make it possible to reduce the cost of heat generation. Further, the data for training the neural network were obtained via industrial thermal installations. Moreover, the combustion parameters varied over a wide range for different combustion regimes.

Let us note the results of an interesting paper [32], one of the authors of which is the author of this review, K. Osintsev. The article examines the properties of coal–water fuel during its transportation in conditions of negative ambient temperatures, while using combined modeling: physical and computer. The article notes the need to use neural network theory methods and models, which can dramatically reduce the thermal and economic costs of transporting coal–water fuel. In this article, mathematical models for creating a control unit for a transport system for pumping water–carbon fuel was developed. At the same time, neural network algorithms were used, which made it possible to take into account implicit dependencies in the operation of the transport system. Examples of such dependencies are the size of coal particles, fuel consumption, pressure in the pipeline, the temperature difference between the pulp and the surrounding air, and the effect of these parameters on the adhesion of coal particles to welds and valves. Accounting for these dependencies make it possible to reduce the likelihood of an emergency. When carrying out physical modeling, the values of the fluidity of coal–water suspensions were measured, and the costs of electricity for pumping fuel under various modes of operation of the transport system were determined. The optimal structure of the coal–water pipeline transport system and effective methods of its management were determined and recommended for practical use. Based on neural network methods, a highly efficient automatic control system for a pipeline transport complex was developed in the article.

The scientific novelty of the article lies in the development of a fundamentally new design of a coal–water fuel hydro tracking unit, which is designed to study the effect of the thermophysical and rheological properties of the pumped water-carbon fuel in regard to the processes of heat and mass transfer during cooling and heating. The installation is divided into three lines, through which coal–water fuel with different characteristics are pumped. The modeling process involves the use of two experimental sites. It is proposed to use refrigerant at the first site. In the second site, low-boiling liquid is poured into the heat pump. The article reveals the possibilities of automation in technological pipeline transport. On the basis of the conducted studies the scheme of technological process control and control of its main parameters is offered. The proposed scheme includes elements of an automated electric drive and control based on a multi-zone controller. In addition, the implementation of the controller is based on neural network software that allows one to achieve efficiency gains by reducing unnecessary heat losses. The article may be of interest to specialists in the fields of power and information electronics, electric drives, and automation of technological processes.

The results of the conducted research can be used in industrial pipeline transport systems. This will improve the reliability of such systems. The results obtained are especially relevant for regions with difficult climatic conditions and topography.

In coal-mining regions—which are, in various countries, remote from railways and often within an undeveloped automobile network (for example, mountainous regions)—scientists and specialists are developing high-tech technologies for pumping coal–water fuel and burning coal–water suspensions in thermal power plants. One example is China, which is currently the leader in the use of coal–water technologies. In China, a slurry preparation plant has been built and is successfully operating; further, it supplies water–carbon fuel to the largest Maoming thermal power plant in Asia [81]. Similar projects were successfully implemented in the USSR and have continued to be implemented in Russia at the present time [82].

Coal–water suspensions can be prepared not only from high-quality raw materials for metallurgical production, but also from coal enrichment waste. Coal enrichment is carried out for transportation over short distances and direct flaring. At the same time, the costs for the needs of industrial enterprises are reduced. For the sake of comparison, the share of coal generation in the United States is 52%, in Germany 54%, in China 72%, and in Poland 94% [32].

## 4. Discussion and Future Prospects

### *4.1. Discussion*

The mathematical models considered in this review are used by researchers to describe the combustion process and the process of transporting coal–water suspension [83,84]. Much attention should be paid to the developments that have proven themselves [85,86].

In Kyrgyzstan, a large amount of coal mining waste is generated annually, which is an excellent raw material for obtaining CWF [87,88]. The CWF currently produced is already competitive today both in relation to the consumed coal and in relation to liquid and gaseous fuels used for combustion in thermal power plants and boiler houses [89,90]. The cost of CWF prepared from coal mining waste, in terms of a ton of standard fuel, is 2–4 times lower than the cost of fuel oil and does not exceed 15–20% of the price of the original coal at the place of its production [91,92]. The creation of new types of coal–water fuels will minimize the cost of re-equipment of boiler units of thermal power plants and make them competitive with fuel oil and diesel fuel when burned in boiler units of thermal power plants and boiler houses.

Currently, coal–water fuel [93,94] is a dispersed composite system consisting of finely divided coal (60–65%), water, and a plasticizing agent (which is prepared from coal, coal-containing waste, and coal sludge) [95,96]. The main mass of coal particles in the developed CWF has a size of 10 . . . 200 µm. Such CWF can be used for combustion in boiler units of thermal power plants [97].

Due to the significant content of large particles in CWF and the presence of an inert aqueous phase (up to 60%), thermal stabilization of the ignition zone of such CWF during ignition is required, which is provided by a fuel oil or gas torch, plasma torch arc, or other methods [98]. In addition, the presence of the mineral part of CWF, when up to 20–25%, necessitates the installation of equipment for ash collection and ash removal, which requires serious capital investments for the conversion of boilers in thermal power plants. These reasons are the main deterrent to the wide spread of CWF in many countries [99,100].

Mathematical models [101,102], created at the turn of the century [103,104], largely determined the direction of development for the composition of suspensions [105,106] and the influence of various factors on plasticity [107,108]. First of all, such factors include temperature, pressure, and the fractional composition of the suspension [109,110].

The use of CWF as an alternative to liquid fuels from oil mainly depends on the successful solution of the following physical and technological problems:

- grinding of the initial coal raw material to the level of 10 microns, and below, at energy costs lower than the existing ones (currently these costs are at 30–35 kW/m$^3$);
- deep demineralization of coal suspension to a salt content of less than 2–3%;
- obtaining, on the basis of demineralized coal dispersion CWF, the necessary technological (thermophysical and rheological) properties.

The solution of the tasks set will make it possible to create fuel for boiler houses that do not require re-equipment.

The use of the cavitation effect in the processing of raw materials, as a result of hydrodynamic loads and shock waves arising in the system, leads to a heating of the substance and an increase in pressure; thus, this is what determines the effectiveness of the method.

Along with the above, it is proposed [111,112] to combine the process of fine grinding with coal demineralization. Intensive hydrodynamic cavitation will allow simultaneous deep demineralization of coal, emulsification of the aqueous phase, and the introduction of plasticizing additives.

The experimental works [113,114] carried out and the literature data indicate that intensive mechanical and hydrodynamic treatment leads to:

- the activation of coals due to the disorder of the structure and thus the formation of defects;
- the transition of coal particles to an ultra-dispersed state, which has a high reactivity, increases the rate of heterogeneous processes, and causes a significant change in the equilibrium parameters characterizing the reactivity of the coal substance.

For developing countries, their own energy independence is in the foreground; this is due to the fact that it is the basis for their economic independence from other sectors of the economy, specifically from the future impact of market changes in fuel prices on the spot world market. The authors of this review explored the possibility of using Kyrgyz brown coal and transporting it through a coal pipeline from a mountainous area to an industrial site for thermal utilization in specialized steam boiler units. As the economic analysis showed, specifically for the conditions of the Republic of Kyrgyzstan, the use of coal–water suspensions and coal pipelines at rising prices for natural gas is economically justified.

According to a review of the works of the authors involved in coal–water suspensions, it is more specifically confirmed that the construction of a coal pipeline is economically justified:

- when it is indispensable for any other modes of transport due to the tendency for spontaneous combustion or the high-water content of the fuel;
- when, due to the conditions of the terrain, it is possible to reduce the length of the pipeline transport main compared to rail or other modes of transport, while hydraulic transport is especially favorable in mountainous or rough terrain if there is an excess of the geodetic height of the supplier in comparison with the consumer;
- with the remoteness of fuel production areas from the places of its consumption and the absence or weak development of highways and railways;
- in the absence of large reserves of labor in pipeline transport, i.e., they do not exceed 30–40% of the cost of rail and road transport.

The results obtained in the process of research allow us to evaluate the modes and speeds of transport. Additionally, we can evaluate the specific pressure losses when moving finely divided Karakechi brown coal in pipelines and, on this same basis, offer graphic and tabular data that can be used in technological calculations at the pre-design and design stages of the development for a pipeline transport system in Kara-Keche—the industrial site of the state district power station.

Karakechi brown coal is satisfactorily wetted when it is fed into water, the non-dehydrated sludge has sufficient fluidity, can be stored in tanks for a long time, the intake from which must be carried out after hydraulic mixing by the suction devices of the pumps.

### *4.2. Future Prospects*

According to the latest works by Yang et al. [94] and Glushkov et al. [49], the combustion of coal–water is increasingly studied in the scientific community, in particular in China and India [94,95]. With the discovery of breakthrough technologies for the combustion of coal–water suspensions, it will be possible to talk about the construction of coal pipelines. In order to issue recommendations on the efficient use of coal pipeline transport, it is necessary to conduct additional research related to the selection of optimal parameters and modes of transporting these coals through pipelines, including specific head losses, transportation speeds, hydro abrasive wear of pipelines, and grindability of coals during transportation. Separately, it should be noted that studies of the rheological properties of suspensions [87,88] and the construction of their mathematical models are ongoing.

The relevance of the use of coal–water fuel at thermal power plants is due to the emergence of new technologies for its preparation and combustion, which eliminate the previously identified shortcomings. The essence of the new technology for the preparation of CWF is that a mixture of carbonaceous materials with water is subjected to cavitation in special devices, i.e., cavitation dispersers. The result of cavitation treatment, which is characterized by an extremely high level of local dynamic, compression, and temperature effects on the material being processed (up to 2000 °C and 25,000 kgf/cm$^2$), is not only the grinding of the solid component of the mixture to a micron degree of dispersion, but also the appearance of properties on the surface of its particles pronounced hydrophilicity. Difficulties associated with attempts to flare CWF in unsuitable existing chamber furnaces are determined by the need to spray the suspension down to micron sizes and increase the residence time of particles in the furnace due to the increased moisture content [111,112]. Therefore, long-flame and gaseous (highly reactive) low-ash coals were recommended for the preparation of CWF, and it is these coals that are quite successfully burned in the form of CWF [113,114] in China.

Taking into account the results of bench combustion of various types of coal–water fuels using various technologies, as the most versatile and especially suitable for combustion of CWF from low-grade fuels, we made a choice in favor of the technology of CWF combustion in a pseudo-boiling layer of an inert material [115,116]. This option, due to the high thermal stability of the mass of fluidized material, allows the ignition and reaction of the fuel at lower temperatures than in chamber combustion. This factor [117] provides a significant reduction in the generation of highly toxic nitrogen oxides, which is also facilitated by an increased content of water vapor in the reaction zone.

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