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Experimental and Mathematical Investigation of the Thermophysical Properties of Coal–Water Slurries Based on Lignite

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Abstract: The burning of organic fuel is one of the main factors influencing the greenhouse effect on the climate of the planet. The article examines the influence of the properties of lignite and coal–water slurries on the amount of carbon dioxide molecules formed as a result of chemical reactions. The authors give an overview of the results of other researchers in recent years and give the results of their research and development in the field of burning lignite and coal–water slurries in industrial recycling plants. The authors present the results of experimental studies of the thermophysical properties of coal and a coal–water mixture. The results obtained were compared with the results of calculations using a mathematical model and the results of numerical modeling in Ansys. New methods of approximation of step functions were used for the mathematical model. These methods make it possible to reduce errors in the approximation of the functions of the thermal properties of coal. The proposed methods do not have the disadvantages of traditional decompositions of step functions into Fourier series and can be used in problems of mathematical modeling of a wide class of processes and systems. In particular, when determining the coefficient of kinematic viscosity, ash content, and humidity by the method of approximation of the obtained data, the use of new mathematical methods makes it possible to reduce the error in calculations. In addition, data on numerical modeling of hydraulic transport and combustion processes are provided, and a data validation procedure is carried out. The data convergence shown and their location in the selected band of uncertainties satisfy the requirements for verification of experimental data adopted in the European Union and in the Eurasian Union.

Keywords: combustion; organic fuel; boiler furnace; step functions; hydraulic transport

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1. Introduction

The Resolution adopted by the Government of the Republic of Kyrgyzstan on increasing the pace and quantity of local coal production is directly linked to their use by large numbers of consumers, in particular the Bishkek CHP (combined heat and power). First of all, we are talking about increasing the supply of Karakechinsky brown coal to this CHP, and coal–water suspension to hot-water boilers in mountainous areas. Since the thermophysical characteristics of the new coal for the thermal power plant and the new coal–water suspension for boilers are very different from the characteristics of the project Karaganda industrial product, a project is needed to transfer the CHP to industrial combustion of non-project fuel. The choice and justification for the inclusion of combustion systems in the project is associated with the peculiarities of the formation and development of a pulverized coal torch in the furnace, as well as the behavior of the ash and slag residue.

Research in the field of movement and burning of lignite, suspensions, and coal–water mixtures has been carried out in laboratory conditions by scientists, mainly in the coal-mining areas of the planet.

Yuxing Zhang, Zhiqiang Xu, Dinghua Liu, Yang Chen, Wei Zhao, and Guanlin Ren in the article [1] investigated the influence of water and its properties on the composition of a coal–water suspension. The researchers showed the influence of water occurrences in CWS (coal–water suspensions) made of lignite and bituminous coal on slurrying performances.

The most general study of the effect of moisture on the thermophysical properties of coal is given by M.A.A. Ahamed, M.S.A. Perera, S.K. Matthai, P.G. Ranjith, and Li Dong-yin in the work [2]. In this work, coal composition and structural variation with rank and its influence on the coal–moisture interactions under coal seam temperature were shown.

In the study [3], the authors Zhifang Chai, Yangguang Ren, Ruijie Zhang, Laihong Feng, Shucheng Liu, Zhichao Wang, and Ming Zeng touched upon a very important issue during the transportation of coal–water suspensions, namely stability and settling performance of coal–water slurries under vibration conditions. A similar study was conducted by the authors Zhifang Chai, Ming Zeng, Yangguang Ren, Ruijie Zhang, Laihong Feng, and Zhifu Zhao in the work [4].

Concerning the issues of the combustion of a coal–water mixture, the work [5] of authors G.V. Kuznetsov, K.Yu. Vershinina, T.R. Valiullin, and P.A. Strizhak should be noted. This work shows differences in ignition and combustion characteristics of waste-derived oil–water emulsions and coal–water slurries containing petrochemicals.

Shilin Liu, Dengfeng Zhang, Zengmin Lun, Chunpeng Zhao, and Haitao Wang in the work [6] presented an overview of the effect of moisture on the properties of coal.

Separately, it is necessary to highlight the work on the gasification of solid fuel. In the work [7], the authors Jianbin Wang, Jian Chen, Jianzhong Liu, He Liu, Mingxia Wang, and Jun Cheng showed the effect of mixing waste-activated carbon and coal in co-slurrying and CO_2 co-gasification.

In the work [8], authors Jinqian Wang, Jianzhong Liu, Shuangni Wang, and Jun Cheng investigated the slurrying property and mechanism of a coal–coal gasification wastewater–slurry.

Researchers Keboletse K.P., Ntuli F., and Oladijo O.P., in the work [9], gave an overview and showed trends in influence of coal properties on coal conversion processes—coal carbonization, carbon fiber production, gasification, and liquefaction technologies. Similar studies have been conducted by Shucheng Liu, Hongyu Zhao, Tao Fan, Jun Zhou, Xiangyang Liu, Yuhuan Li, Guofeng Zhao, Yonggang Wang, and Ming Zeng in the work [10].

Separately, the works [11,12] on gasification reactions, combustion, and intermediate stages of combustion in a nonequilibrium state should be noted. Authors Lin Li, Shuai Tong, Lunbo Duan, Changsui Zhao, and Zhipeng Shi in the work [11] investigated the effect of CO_2 and H_2O on lignite char structure and reactivity in a fluidized bed reactor. In the work [12], authors Zhenghong Zhao, Tai Zhang, Xiaoshan Li, Liqi Zhang, Zewu Zhang, Yuxiao Chen, Fan Wu, Cong Luo, and Chuguang Zheng investigated the NO formation mechanism of CH_4/NH_3 jet flames in hot co-flow under MILD-oxy condition: the effects of co-flow CO_2 and H_2O.

Studies of the processes of burning and preparation of solid fuels are conducted by scientists from many countries using various mathematical apparatus. In the article [13], the authors describe the use and supply of a coal mixture at an industrial enterprise. Mathematical models of the authors in [14] describe the process of heat exchange and contribute to the improvement of the processes of mixing fuel and oxidizer. In addition, researchers in [15] point to the accuracy of determining the amount of air required for oxidation. Models of fuel combustion [16], supply, and use of solid fuel [17] help scientists to take into account additional factors influencing heat exchange and aeromechanics. The theoretical foundations of combustion processes [16], along with mathematical descriptions [15], confirm the influence of the properties of coal on the amount of emissions and the composition of combustion products. In the coal-mining countries of Asia, the basis of the fuel sector is occupied by lignites [17].

The authors of the article have previously investigated the properties of organic fuels [15], in particular coal [16] and coal–water suspension [17]. The task of all these studies is to give a mathematical description of the combustion process of coal particles or coal–water suspensions (Figure 1).

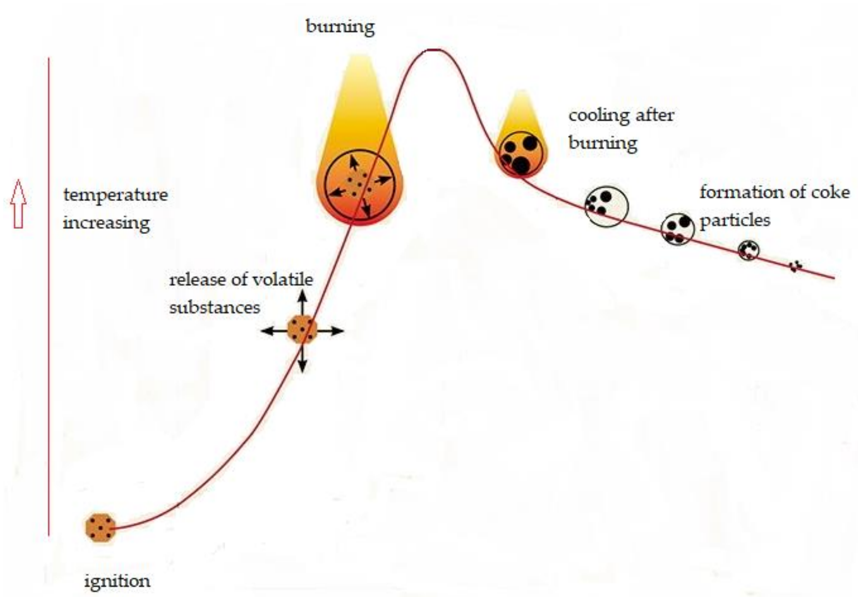

Figure 1. Combustion of a coal particle.

The research is reduced not only to physical and chemical experiments, but also to the construction of a new methodology based on the methods of approximation of step functions with an estimate of the error of approximations. Step functions are widely used in various fields of scientific research. The traditional areas of their application are technical and mathematical disciplines; for example, the theory of automatic control, electrical engineering, radio engineering, the theory of information and signal transmission, equations of mathematical physics, the theory of oscillations, differential equations, and many others [18]. Approximation methods were used to describe mathematical regularities [19]. Such methods are also applicable to the theory of heat transfer [20].

Systems with stepwise characteristics and functions are referred to as essentially nonlinear structures, emphasizing the complexity of obtaining solutions for such structures. Despite the simplicity of step functions by sections, the construction of solutions in problems with step functions over the entire domain of definition requires the use of special mathematical methods, for example, the method of stocking with linking solutions by sections and switching surfaces. The application of the method of stocking, as a rule, requires overcoming significant mathematical difficulties, and quite often the solution is obtained in a cumbersome form, in the form of complex expressions.

The existence of the Gibbs effect leads to extremely negative consequences of using a partial sum of a trigonometric series as an approximating function, for example, in radio engineering, in the field of signal transmission, and in a number of other practical examples.

Previously, the authors of the article have already shown the effectiveness of using new approximation methods in application to thermal power facilities and systems [16,19].

1.1. Information on Developments in the Scientific Field on the Preparation of Coal Dust and Its Further Combustion

Scientists around the world have studied the processes of burning and producing solid fuel. The most comprehensive overview of the preparation of coal dust at thermal power stations can be found in [13]. One of the main conditions for effective and high-quality burning of solid fuel is taking its polyfractional composition into account, which can be confirmed by mathematical models presented in [14]. The presence of a sufficient amount of oxygen as an oxidizing agent and the fineness of grinding are mentioned in [21]. There are various models of burning [22], screening, and preparing solid fuel [1,23]. Moreover, we should not disregard the basics of practical combustion theory [24], which were developed alongside studies in mathematical modeling [21]. The lack of natural gas in separate coal-producing countries gave rise to the development of new methodological approaches to the screening and burning of lignites. One of the major works in this field is [25], which also first raised the problem of dust screening and approximation of the results obtained, which later was reflected in the above-mentioned source [13]. Modern computer programs of mathematical modeling of coal dust burning take into account thermal and physical characteristics of fuel and average equivalent particle size. It also should be noted that existing software provides an understanding of the temperature field distribution, velocities, and concentrations, which are connected with known dependences [21,22], though accuracy and validity of the obtained results does not always satisfy the criteria necessary for the initial design of a boiler unit or to make changes to the dust production system. In any case, it is necessary to conduct experiments and compare them with the results of computer modeling. The authors of [26] mention that it is impossible to implement standard methods with coal particles after micro-grinding, which can be proved by the experimental results [27]. The same scholars propose to take into account the influence of particle size on the absolute ignition temperature according to the well-known equation [27] based on the law of conservation of energy which can be employed for a single particle:

$$\frac{m_p \cdot C_p}{4\pi r_p^2}\frac{dT_p}{dt} = \varepsilon \cdot \sigma \cdot \left(T_{rad}^4 - T_p^4\right) + \alpha_{con} \cdot \left(T_g - T_p\right) + \frac{Q \cdot H}{4\pi r_p^2} \tag{1}$$

where m_p is the mass of a single particle, kg, C_p is the heat capacity of a particle, J/(kg·K), r_p is the equivalent size of a particle (a radius in this case), m, T_p is the absolute temperature on the particle surface, K, ε is the degree of particle blackness, σ is the Stefan–Boltzmann constant, W/(m^2·K4), α_{con} is the convective heat transfer coefficient, W/(m^2·K), T_g is the absolute temperature of gas medium, K, T_{rad} is the absolute temperature of the radiation volume, K, Q is the specific thermal effect of oxidation of carbon residue, J/kg, and H is the oxidation rate of carbon residue, kg/sec.

1.2. Modern Hypotheses and Their Confirmation by Researchers

The scientific developments of L. Rosendahl, conducted relatively recently, show that the theory of heat and mass transfer, in particular the sieving and burning of coal dust, has its drawbacks in relation to experimental studies of boiler installations. L. Rosendahl and M. Mando presented the results of the research in the form of a developed model [28]. Researchers, for example T. Asotani [29] and his colleagues, proposed a hypothesis of the behavior of coal particles in the air flow, and this hypothesis was partially confirmed by the developed mathematical model, which is consistent with the results of L. Rosendahl and M. Mando [28]. The hypotheses considered in the review have been confirmed through the construction of mathematical models. These models fully correspond to each other, as well as to the basic physical laws, in particular, the equations of conservation of mass and energy, as well as the boundary conditions of heat exchange processes.

Thus, with the known modern models and proven hypotheses [28,29], at least one unsolved problem arises, namely, increasing the efficiency of the mathematical apparatus used when considering ideal conditions for grinding coal dust and its combustion. The solution of this problem will lead to the achievement of the goal of the research work—simplification of mathematical calculations of dust sieving and combustion in real conditions of the boiler unit using piecewise linear functions. Piecewise linear functions, in contrast to the continuous description of dust sieving and sequential entry into oxidative combustion reactions developed by the authors, allow for the smallest changes in the composition of the particle mass after grinding and sieve analysis. This leads to a positive trend of operational accounting for the slightest change in the fractional composition, while the continuous function or the Gauss curve is still a spline line well-chosen for ideal or theoretical conditions of grinding and coal dust combustion.

1.3. The Purpose and Objectives of the Study

Throughout experiments related to the dust production of a new type of solid fuel or production of a solid fuel in new conditions, the coefficients b, n may change. Mathematical modeling of solid fuel preparation and combustion can be performed without costly tests and experiments.

The purpose of the study is to develop new methodological approaches to dust preparation and combustion of separate particles including a polyfractional ensemble.

To achieve this, the authors divided the study into separate scientific tasks.

1. Transform the standard function of coal dust analysis and combustion into a continuous integrated function for further application in the mathematical modeling of coal dust burning in an ensemble.
2. Apply the density of normal distribution of probable deviations from the mean for mathematical description of analysis and combustion; use the Gauss curve according to the selected type of function.
3. Normalize the function describing the ensemble of particles gradually undergoing exothermic oxidation while burning in a torch.
4. Use differential curves in piece-linear functions or their approximation of recursive functions for reducing errors in mathematical modeling.
5. Verify the adequacy of mathematical modeling methods; compare the calculation errors of the standard method with the method developed by the authors.

1.4. Scientific Novelty of the Methods and Methodology of the Research

The scientific novelty of the research lies in the improved theoretical and methodological base for coal dust investigation using analysis and heat exchange during coal dust combustion. This base is founded on the concept of a continuum as a continuous medium in which the processes of combustion and heat exchange are investigated. We developed and implemented a method of mathematical modeling based on new approaches to approximation of piece-linear functions. This method increases the accuracy and validity of the results being adapted to possibilities of modern technologies, the effect produced on fuel and air flow, regulation of thermal characteristics of the flow, and the quality of the supplied coal dust.

2. Research Methodology

With regard to the hydrotransportation of coal and water–coal mixtures, the authors propose the following methodology based on the basic laws of physics and hydraulics. The calculations were carried out as follows.

With the specified parameters ρ_{mix}, v, c_p, D, V, i_{wat}, and i_{mix}, an additional slope Δi was determined

$$\Delta i = i_{\mathrm{mix}} - i_{\mathrm{wat}} \quad (2)$$

where i_{mix}—specific pressure losses during the movement of the hydraulic mixture (experimental data), and i_{wat}—specific pressure losses during water movement (experimental data).

According to the Darcy–Weisbach formulas, specific pressure losses were calculated during the movement of water

$$\mathrm{i_{mid}} = \lambda_{\mathrm{s}} \mathrm{V}^2 (4\mathrm{gD})^{-1} \quad (3)$$

where i_{mid}—middle specific pressure losses during water movement (calculated data), and λ_{s}—hydraulic friction coefficient for hydraulically smooth pipelines:

$$\lambda_{\mathrm{s}} = 0.31[(\lg(\mathrm{Re}) - 1]^{-2}, \quad (4)$$

$$\lambda_{\mathrm{s}} = 1.1[(1.8 \lg(\mathrm{Re}) - 1.5]^{-2}. \quad (5)$$

Based on the values i_{mid} and Δi, specific pressure losses were determined during the movement of the hydraulic mixture through hydraulically smooth pipelines

$$i_{mix.r} = i_{mid} + \Delta i. \quad (6)$$

As a result of such processing of experimental data, graphical dependences of specific pressure losses on the speed of transportation in pipelines with a diameter of 200–450 mm at a mass concentration of a hydraulic mixture equal to 50% are shown.

Data with a sufficient degree of approximation can be used in the selection of parameters and calculation of the hydraulic transport system.

For hydraulic mixtures composed of finely ground coal, the critical speed of movement is not a determining value.

The speed of transportation is selected based on technical and economic considerations, minimal energy consumption for moving solid material, and minimal wear of pipelines.

In particular, A.E. Smoldyrev recommends the following rates of transportation of coal–water suspensions (Tables 1 and 2).

Table 1. Transportation rates of coal–water suspensions (beginning).

Diameter D, m	0.10	0.15	0.20	0.25	0.30	0.50
Speed V, m/s	0.70	0.85	1.0	1.2	1.4	1.5

Table 2. Transportation rates of coal–water suspensions (continued).

Diameter D, m	200	300	400	500	600	700	800
Speed V, m/s	1.15 1.35	1.25 1.45	1.35 1.55	1.40 1.65	1.50 1.80	1.60 1.95	1.65 2.00

To eliminate the noted shortcomings in the mathematical description of the processes of coal–water suspension transport when determining the kinematic viscosity coefficient, new methods of approximation of step functions based on the use of trigonometric expressions in the form of recursive functions are proposed in this paper.

Consider, for example, the step function (7) in more detail.

$$f_0(x) = \text{sign}(\sin x). \quad (7)$$

This function is often used for an example of using Fourier series, and therefore it is convenient to take this function for a comparative analysis of the traditional Fourier series decomposition and the proposed method.

The decomposition of Function (7) into a Fourier series has all the disadvantages described above. To eliminate them, it is proposed to approximate the initial step function, a sequence of recursive periodic functions

$$\{\ f_n(x) \mid f_n(x) = \sin((\pi/2) \cdot f_{n-1}(x)),\ f_1(x) = \sin x;\ n-1 \in N\ \} \subset C^{\infty}[-\pi, \pi] \quad (8)$$

The graphs of the original function (thickened line) and its five successive approximations in this case have the form shown in Figure 2. As we can see, even with relatively small values, when using the iterative procedure (8), the graph of the approximating function approximates the original function (7) quite well. At the same time, the approximating functions obtained using the proposed method are devoid of the disadvantages of Fourier series expansion. The Gibbs effect is completely absent.

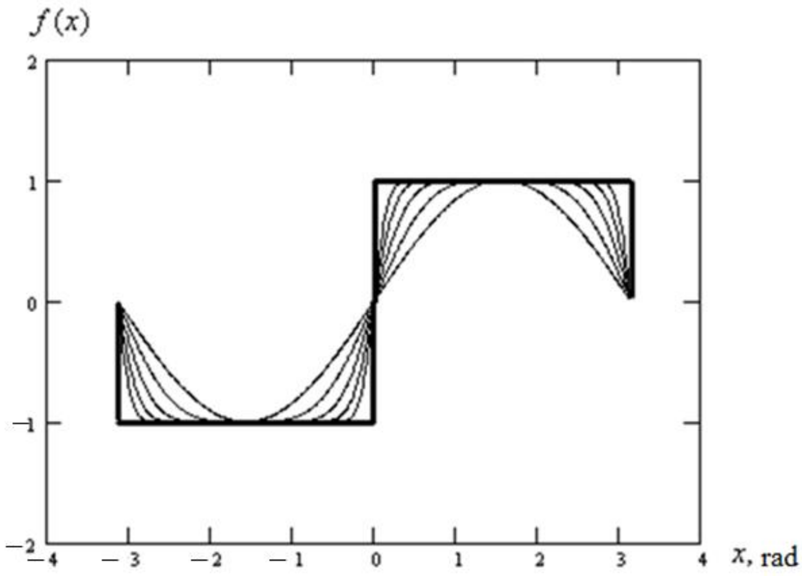

Figure 2. Graphs of the original function and its five successive approximations.

We note some features of the proposed approximating iterative procedure.

Note that the functions $f_n(x)$ and $f_0(x)$ are odd and periodic with a period of 2π.

Functions $f_n(x + \pi/2)$ and $f_0(x + \pi/2)$ are periodic. Therefore, it is sufficient to consider the sequence of approximating function (7) on the segment $[0, \pi/2]$.

Accept $\{f_n(x)\} \subset L_2[0, \pi/2]$ and $\{f_0(x)\} \subset L_2[0, \pi/2]$. Since

$$\sup_{n\in N} \sup_{x\in[0,\pi/2]} |f_n(x)| = 1 < \infty \tag{9}$$

due to limited functions $f_n(x)$ and

$$\sup_{n\in N} \underset{0}{\overset{\pi/2}{Var}} f_n = 1 < \infty, \tag{10}$$

due to the monotony of functions $f_n(x)$ on the segment $[0, \pi/2]$. Then, based on the Helly theorem in the sequence $\{f_n(x)\}$, it is possible to extract a subsequence converging at each point $[0, \pi/2]$ to some function f with

$$\underset{0}{\overset{\pi/2}{Var}} f \le \overline{\lim_{n\to\infty}} \underset{0}{\overset{\pi/2}{Var}} f_n \tag{11}$$

Moreover, as such a function *f*, the original function can act $f_0(x)$.

For experimental studies on the combustion of lignite and coal–water suspensions, coal from the Karakechinsky deposit in the Republic of Kyrgyzstan was used.

The developed method was used to determine the coefficient of kinematic viscosity, ash content, and humidity by approximating the data obtained using new mathematical methods to reduce the error in calculations.

During the pilot combustion of small batches of Karakechin coal supplied to the Bishkek CHP by motor transport, they faced the problem of rapid oxidizability of freshly extracted fuel with loss of heat of combustion: $\Delta Q^{daf}{}_{l} = Q^{daf}{}_{l\text{theor}} - Q^{daf}{}_{l\text{real}} \approx 19.3 - 15.1 = 4.2$ MJ/kg, where $Q^{daf}{}_{l\text{theor}}$, $Q^{daf}{}_{l\text{real}}$ is the heat of combustion of coal freshly extracted and delivered to the Bishkek CHP warehouse, MJ/kg. High content of CaO > 15% in the rock leads to overgrowth of wet ash traps and channels by hydrosol removal with the compound $CaCO_3$. It is advantageous for the CHP to use fuel with increased heat of combustion, since the load of fuel supply equipment and mills is reduced, and the costs for its own needs are reduced. This is possible with the delivery of freshly mined coal in a transport closed from direct solar irradiation and loading the fuel supply "from wheels", without storage in an open warehouse. The issues of increasing the reliability of ash collectors must be addressed in conjunction with increasing their efficiency. This requires a more detailed study of the process with the development of individual recommendations and technical proposals.

Stable combustion of coal dust particles in the torch of a multifunctional burner without illumination by highly reactive fuel is achieved with the content of volatile substances per combustible mass $V^{daf} \geq 20\%$.

At $V^{daf} \geq 40\%$, according to the safety standards of dust preparation, recirculation gases should be supplied to the mills, reducing the oxygen concentration to $O_2 \leq 16\%$. The subsequent removal of inert ballast with dust into the furnace and its involvement in the ignition process leads to an additional decrease in the temperature of the torch. When entering the mills, and then into the furnace together with the brown coal dust with $V^{daf} \geq 40\%$, the recirculation gases change the characteristics of not only combustion, but also heat exchange processes. In particular, the temperature of the combustion products removed from the boiler and the heat loss with the outgoing gases increase.

3. Experimental Procedures

3.1. Investigation of the Properties of Coal–Water Suspensions

In some projects [1,4] for industrial use of CWS (coal–water suspensions), authors focus on coal–water slurries prepared from high-quality low-ash coals, in particular, bituminous coals, with heat of combustion ${Q^{daf}}_l \geq 35$ MJ/kg, the content of mineral inclusions per dry mass $A^{daf} \leq 2\%$, and the release of volatile to combustible mass $V^{daf} \geq 40\%$. The suspension of these coals, having a high value of calorific value ${Q^{daf}}_l \geq 24$ MJ/kg at working humidity $W^{daf} \leq 30\%$ and the maximum size of solid particles ~200 microns, can be economically transported from the place of coal mining and cooking to the user, stored for a long time, and not stratified. The project developers point out the advantages of using CWS at pulverized coal thermal power plants associated with simplifying the technology of receiving, storing, and supplying fuel to boilers, and note the improvement of the ecological condition of the pulverized coal thermal power plant location area after their transfer to CWS by reducing the release of fine ash and carcinogenic nitrogen oxides into the atmosphere. The production and supply of highly reactive CWS is associated with minimizing the total costs of hydraulic extraction, preparation, hydraulic transport, and the cost of solid fuel. Many issues of slurry combustion organization that are important for flare furnace designers, including the specifics of ignition and behavior of solid fuel particles in real industrial installations, are practically not disclosed.

Despite the actively conducted research on combustion, which began in the 1950s, in the absence of industrial experience, it was seriously difficult to make forecasts for the organization of exothermic processes on boilers when using the source fuel with different heat of combustion, ash content, and particle sizes. At the same time, CWS with significantly degraded (relative to the CWS of bituminous coal) thermophysical properties and particle sizes up to 350 microns were used (Figure 3a,b). A detailed description of boilers and installations for the preparation, feeding, and spraying of CWS, as well as the results of comparative combustion of dust and suspension, were previously given in the open press.

The tests carried out showed that a polydisperse drip torch was formed in the furnace when spraying CWS. The droplets, when in a high-temperature furnace environment, warmed up, moisture evaporated from them, volatile substances came out, and the warmed up volatile substances and solid coke residue began to react with oxygen supplied through the burners of air (ignited) with heat release and an increase in temperature. Subsequent oxidation (burning) of the drip coke residue was accompanied by sintering of its individual particles into ash–coke conglomerates. The transition from pulverized coal to slurry combustion was accompanied by an increase (stretching) of the length of the ignition site and a decrease in its temperature level. This is typical for combustion with passivation of the oxidative process at the ignition site with an inert ballast: recirculation gases, steam, water, an excessive amount of mineral inclusions, as well as their combination.

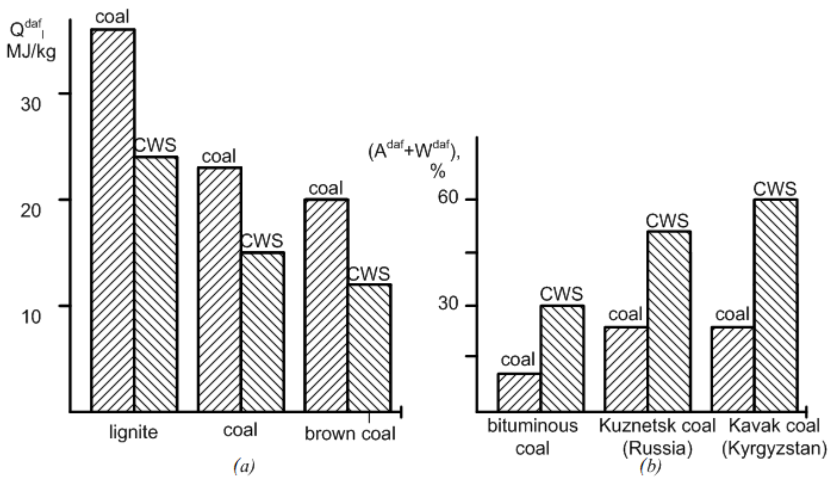

Figure 3. Comparison of the characteristics of dust and CWS of various coals: (**a**) heat of combustion; (**b**) total ballast of mineral inclusions and moisture.

3.2. Experimental Study of the Properties of Coal–Water Suspension

From Figure 4 presented as an example, it can be seen that during the testing period of the TP-35 boiler, the bulk of the pulverized fuel, in particular Kavak coal, burns out on the horizontal section of the torch in front of the burners from their output section l = 0 up to the mark lf, where the degree of burnout a = 0.9. The maximum temperature level Tf is also developing here; in the vertical section, the torch is cooled to the experimental value fixed at the outlet of the furnace T = Tf = 1230 K (parameter T/Tf = 1.0; a = 0.95). When a pulverized suspension from the same Kavak coal is fed into the furnace, the nature of burning changes dramatically: the ignition site lf increases by 3–4 times, and the maximum temperature Tf reduces by 200–300 K. Passivation of ignition causes a delay in the combustion process and volatile and coke residue. In the output window of the furnace, the temperature of the torch becomes higher (T/Tf > 1.0), and the degree of burnout is reduced to $a \leq 0.82$.

Burnt-out ash–coke conglomerates, heavier and larger in comparison with individual dust particles, were captured with great efficiency in conventional ash collectors in front of smoke pumps and chimneys, causing a decrease of up to 5–8 times in the concentration of fine fly ash in the combustion products discharged into the atmosphere. In the presence of water ballast, oxidative processes were passivated, including the formation of nitrogen oxides.

According to the results of the tests of the PK-40 and TP-35 boilers, the design of the TPE-214 boiler of the Novosibirsk CHP-5 was adopted for CWS, which provides, in addition to its main work on dust, the possibility of working out suspension combustion.

Focusing on the CWS with a maximum particle size of ≤350 microns, a thermal imbalance was incorporated into the boiler design according to $\Delta(q_2 + q_4)$ for suspension and pulverized coal torches, where q_2 and q_4 are heat losses with outgoing gases and mechanical losses with insufficient combustion of fuel, %. The beginning of the stratification of CWS in pipelines and storage facilities for an indefinite time "froze" the idea of using unconventional liquid fuel at the country's energy boilers, and this essentially ended the government program itself.

Recent reports of ultra-stable new-generation CWS with over-crushed fuel particles up to 3–40 microns and good transportable characteristics were obtained in ultra-economical shredding plants of a new generation.

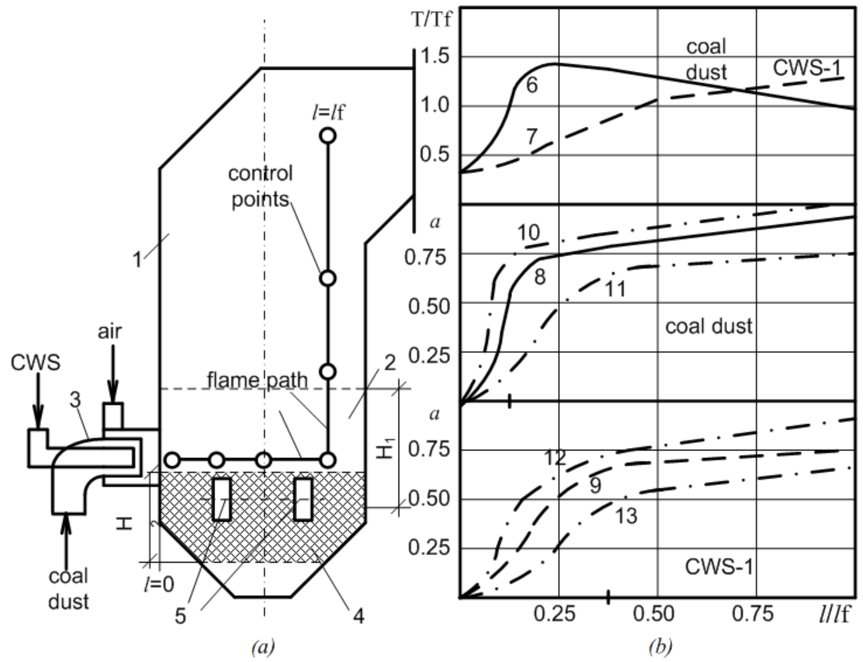

Figure 4. The nature of the change in dimensionless temperatures (T/Tf) and the degree of fuel burnout (**a**) in pulverized coal and suspension flares of Kavak brown coal on the TP-35 boiler: 1—furnace; 2—active combustion zone for dust and CWS in experiments; 3—burners for burning dust and CWS in experiments; 4, 5—calculated active combustion zone and burners for fine CWS; (**b**) 6, 7, 8, 9—integral curves; 10, 12—R < 90 microns; 11, 13—R > 90 microns; 6, 8—burning of dust with a maximum particle size of 350 microns; 7, 9—burning of CWS with a maximum particle size of 350 microns (**b**).

Earlier, it was found that the largest fractions with R $\geq$ 90 microns make the main contribution to the deviations of the integral values of the degree of burnout. This applies to both dust and suspension torches. Conglomerate particles of a suspension torch with R < 90 microns, reaching the output window of the furnace with a degree of burnout up to a = 0.90–0.95, and particles with R $\leq$ 40 microns, burn almost completely. The degree of burnout of particles with R $\leq$ 40 microns at the end of the horizontal section of the suspension torch was $a \approx 0.90$, and corresponded to the design value for particles of the average integral size of the pulverized coal torch. Volatile substances present in the initial coal are partially dissolved in suspension water, partially stored in the dust component, and also as in a pulverized coal torch, they burn primarily together with coke fines.

Additional calculations on the hypothetical composition of the CWS of Kavak coal with W^{daf} < 50% and particle sizes $\leq$ 3 microns show that the lightless mode is achieved when $W^{daf} \approx 40\%$. Continuation of illumination at $W^{p} \approx 40\%$ increases heat dissipation and temperature Tf near the burner; it is almost already up to the levels characteristic of vacuum burning. Variants with illuminated diesel fuel in the first approximation imitate a highly reactive CWS with increased integral heat of combustion enriched with highly reactive components. Such a product correlates well with a mixture of waste oil products and waste oils with the same coal chips, which are subject to flare disposal on boilers. According to the definition of specialists developing new unconventional fuels, such a mixture refers to composite liquid fuels. In reality, the combustion of fine-dispersed CWS in the form of condensed sludge (coagulant) with fuel particles $\leq$ 40 microns at $W^{daf} \approx$ 40–50% after hydrotransportation of coal fractions up to 25 mm (the second direction of using CWS) was worked out on the boiler PK-40 Belovskaya GRES. Sludge and coal dust sprayed by specially designed nozzles with air through individual burners placed on the side walls were injected into the furnace in a ratio of 20/80 in terms of heat release. It is shown that the re-grinding of the initial fuel particles practically does not affect the nature of droplet formation during atomization and the formation of ash conglomerates, and all the coal fines entering the furnace with CWS burn out ($a \approx 1.0$).

Moisture transport flows cause an increase in the temperature of the exhaust gases and the corresponding heat loss Δq_2 = 0.20–0.25%. Having a small loss on Δq_2 and the additional losses on the compression of the sprayed air were compensated by the "consumer" by improving the environmental performance of the boiler and reducing the cost of fuel in the sludge. The "supplier" of coal reduced the total costs of hydraulic transport and the fee for liquid polluting discharges. Subsequently, in connection with the transfer of the boilers of the Belovskaya GRES to a new environmentally cleaner technology for burning coal dust, exothermic sludge disposal was abandoned.

The considered cases of comparative combustion of coal dust and CWS with a high rock content ($A^{daf} \geq 10\%$) are linked to boilers, which provides for the removal of solid burnt particles from under the furnace and behind the boiler. The design of boilers must be associated with the type of main fuel. Auxiliary burners and nozzles are assembled in the dimensions of the active dust burning zone. When designing new boilers running on CWS as the main type of fuel, the choice of the temperature regime and the size of the heating surfaces, as well as the temperature of combustion products, including exhaust gases, is carried out taking into account the additional ballast volume of water vapor with minimizing heat q_2 loss and elimination of deviation by Δq_2, appearing during tests on existing pulverized coal boilers. When using low-reaction CWS, it is possible to introduce special additives that increase the burning activity of CWS in drops, as well as the temperature level in the active combustion zone.

3.3. Experimental and Numerical Simulation of the Combustion Process of Coal and Coal–Water Suspension

Studies on numerical modeling of coal and coal–water slurry combustion processes were carried out (Figures 5 and 6).

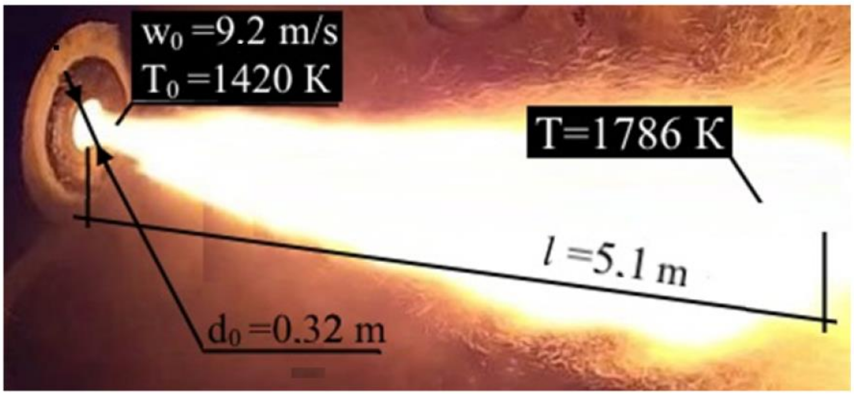

Figure 5. Experimental study of combustion on the E-160 boiler.

The development of computer technology has allowed us to bring engineering calculations to a qualitatively new level. When solving computational problems, the engineer considers various methods and approaches that allow obtaining a high-quality result in an optimally short time. Modern practice proves that the use of software systems based on the finite element method allows you to achieve your goals. The capabilities of the ANSYS software package allow you to obtain full-fledged pictures of physical processes in the furnace chamber; to perform calculations of the movement of particle trajectories in the entire volume of the combustion chamber; and to obtain color maps of temperature fields, heat fluxes, and changes in particle velocities at the level of all tiers of burning pulverized coal fuel. The initial stage of solving the problem is reduced to creating a computational geometry in CAD (computer-aided design), which is the basis for a grid mathematical model. Modern CAD systems, such as SolidWorks, Autodesk Inventor, etc., allow the exchange of computational geometry with the ANSYS software package at the parametric level.

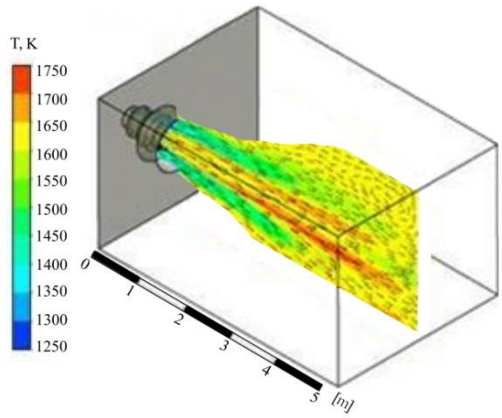

Figure 6. Combustion of coal–water suspension.

The initial data are as follows: carbon (C) = 35%, hydrogen (H^{daf}) = 3%, oxygen (O^{daf}) = 12, moisture (W^{daf}) = 35%, nitrogen (N^{daf})= 0.5%, sulfur (S^{daf}) = 0.5%, and ash (A^{daf}) = 14%.

Using the EDM model together with the Lagrangian particle model makes it possible to simulate the processes occurring in the furnaces of power boilers, including evaluating the optimal degree of coal grinding.

Since very fine grinding is uneconomical and often leads to violations of the design in combustion mode, the disadvantages of the vortex decay model include that it incorrectly predicts the level of nitrogen oxide emissions, and also simulates the ignition process of mixtures with insufficient accuracy. However, these very important aspects of combustion should not be neglected.

As opposed to unlimited high speeds ("fast chemistry"), the Finite Rate Chemistry Model (FRC) takes into account the consequences of the finiteness of the rate of chemical reactions. It allows us to calculate the reaction rates described by the molecular interaction between the components of the liquid.

The FRC model can be combined with the vortex decay model when calculating flames in which the rate of chemical reactions weakly competes with the rate of mixing of reagents.

The second strategy of combustion modeling in ANSYS CFX is based on the assumption that the turbulent flow can be adequately described by statistical methods. If, for example, the Probability Density Function is known for any parameter of the reacting flow (velocity, temperature, mass fractions of individual components) at some point in space, then the average values of the local properties of the flow can always be easily calculated [20].

The combustion modeling strategies discussed above, and their components, are constantly being improved. For example, in the latest version of CFX, it has become possible to use new turbulence models in the calculations of combustion processes, such as Large Eddy Simulation (LES), a model of large vortex structures, and Detached Eddy Simulation (DES), a model of a free vortex. Scale Adaptive simulation (SAS), a model that takes into account the scale of turbulent pulsations, is under development. The SAS model combines two alternative approaches to writing the Navier–Stokes equations: LES and RANS. In the first case, a special procedure is used to exclude sub-grid vortices from the calculation, that is, vortices whose size are smaller than the cells of the calculated grid. The second option involves writing the transport equations, a time-averaged flow with all the assumed turbulence scales.

Computer modeling is becoming an increasingly important element of combustion research and the design of various devices using the combustion process. It can be expected that its role will increase in the future. At the same time, it would be wrong to talk about the complete replacement of experimental studies with numerical calculations—here we are talking about design approaches that should complement each other.

As a result of analytical calculations, the dependence of the parameters of a heterogeneous torch on the mathematical description of the fractional composition of coal dust is substantiated; the characteristics of the combustion process that were not previously taken into account in the theory of heat exchange are revealed; new methodological approaches to the theory of heat exchange in the furnace of a boiler unit are theoretically confirmed.

The results of theoretical studies were tested by the authors at operating thermal power plants, in particular when burning coal dust in E-220 boilers. Comparative analyses and experimental studies on samples of coal dust of various compositions were carried out in the laboratory of Thermal Power Engineering of the Scientific and Technical Center under the Ministry of Energy of the Kyrgyz Republic. The movement of coal dust along the sampling tubes of the devices was taken into account, as well as the degree of grinding in roller and hammer mills. The results showed good convergence within the engineering error of theoretical and experimental data.

The length of Lf = 5.1 m and the temperature of the torch at the length of the torch Lf during operation of the boiler E-220 was T = 1786 K. The data are given depending on the steam capacity of the boiler unit at the nominal load of the boiler Dnom = 61 kg of steam per second. In addition, the data are given when burning Kyrgyz coal with a heat of combustion of 27,820 kJ/kg.

Analysis of the calculated and experimental data showed a discrepancy between them of 4–5%, which could be explained by some error when conducting experiments at high temperatures in boiler installations, for example, re-emission and high dustiness of the torch in the furnace space.

In addition, the possibility of considering a flare as a continuous medium is theoretically confirmed; prospects for identifying the distribution of adiabatic temperature along the length and height of the flare continuum in the zone of intense combustion of the furnace chamber of the boiler unit are shown.

It should be noted that computer modeling was also carried out in a special program, which took into account the boundary and initial conditions as during combustion coal dust in the furnace of the boiler unit E-160 (Figure 6).

The analysis of the computer simulation data showed a discrepancy with the calculated data of 3–4%, and with the experimental data of 5–6%.

Authors note that computer modeling of combustion processes and movement of combustion products in Ansys showed similarities with the combustion and movement of particles of liquid fuel, such as fuel oil or diesel fuel. This similarity was noted earlier during physical experiments.

During the mathematical modeling of the combustion process in ANSYS, we built a solid three-dimensional model of the channel of the burner device and laid a grid on it (Figure 7).

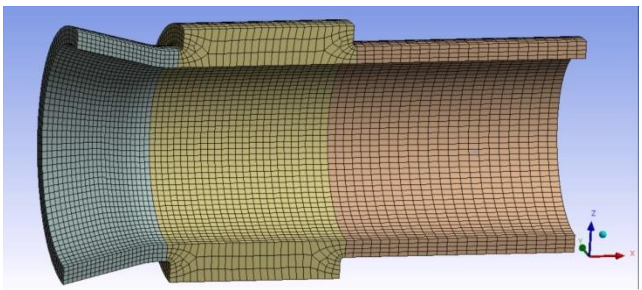

Figure 7. A grid laid on the solid model of the burner device.

The flow of the fuel and air mixture was d in two cases, namely with 12 percent and 16 percent oxygen. This condition was necessary for complete modeling of the mixing process and chemical reactions at different distances from the cut of the burner, since the burners are located in two tiers above each other on a real boiler unit. Thus, on the lower tier, the condition is fulfilled, under which the fuel burns out immediately and completely with 16 percent oxygen in the air. At the same time, on the second tier, at a certain distance from the cut of the lower burners, oxygen is gradually consumed, and its content approaches 12 percent. In the real boiler unit, the fuel burn-up degree can be estimated not only by the oxygen content but also by the presence of CO in the combustion products. In fact, the higher the CO content is, the lower the degree of the coal dust burn-up gets, and the worse the process of the organic fuel combustion in the furnace of a boiler unit is organized. These data are collected by the neural network; the signals are sampled according to the technology developed by the authors.

As a result of the mathematical modeling of the coal dust combustion process, we obtained approximately equivalent fields, shown in Figures 8–10. Figure 8 shows the velocity fields for the lower tier of the burner devices with 16 percent oxygen concentration in the air. Figure 9 shows the concentration of carbon oxide, and Figure 10 shows the concentration of nitric oxide.

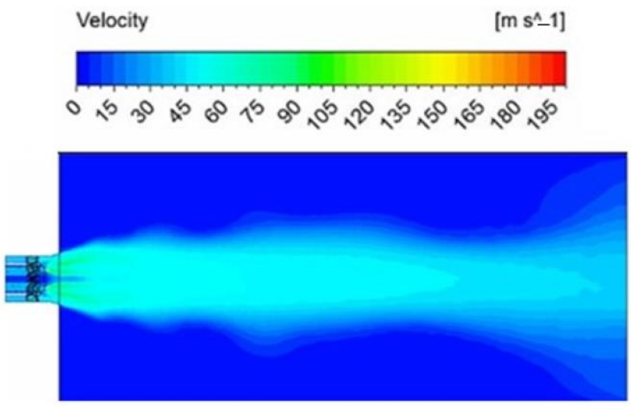

Figure 8. Building a mathematical model of the velocity distribution based on the data collected by the neural network.

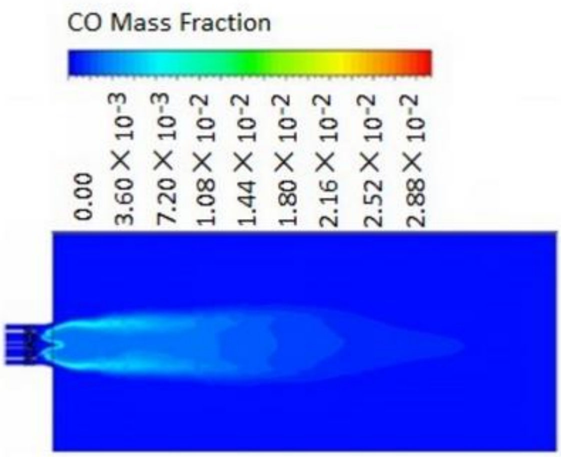

Figure 9. Building a mathematical model of the carbon oxide distribution based on the data collected by the neural network.

The authors presented the results of mathematical modeling in the ANSYS computer environment. The empirical data obtained from similar devices using the developed sampling technology were used as initial conditions.

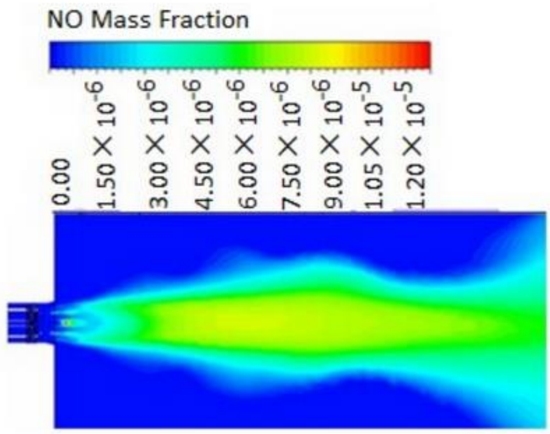

Figure 10. Building a mathematical model of the nitric oxide distribution based on the data collected by the neural network.

3.4. Processing of Experimental Results

Such methods and mathematical dependencies, as well as experimental data, must pass the verification procedure. To do this, it is proposed to use the error integral:

$$\theta(u) = \exp(-0.5u^2)/(2\pi)^{0.5}. \quad (12)$$

In this formula, u is the deviation (standard):

$$u = (x_i - \xi)/(\xi\sigma). \quad (13)$$

The normal distribution can be represented as a Gaussian curve, in this case 3D (Figure 11).

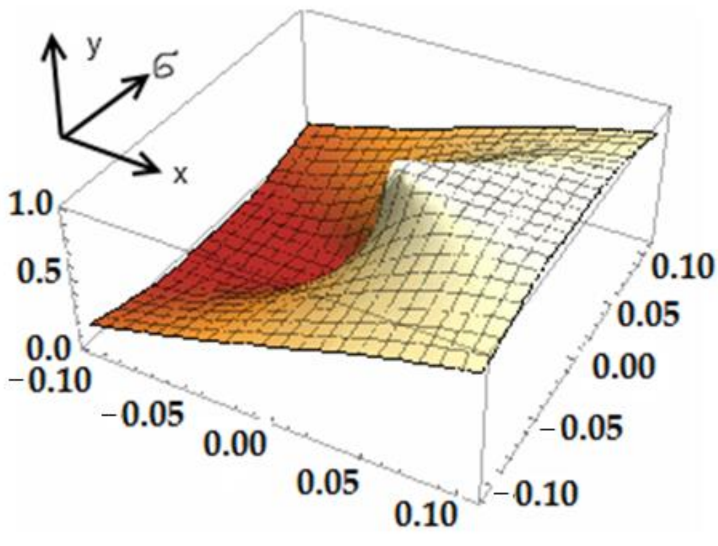

Figure 11. Distribution of the random value of deviations $y = \theta(u)$, where $x = u = (x_i - \xi)/(\xi \cdot \sigma)$, with center ξ and dispersion σ^2.

3.5. Comparison of Experimental Data Taking into Account New Approximation Methods

Figure 12 is based on the data presented in Table 3.

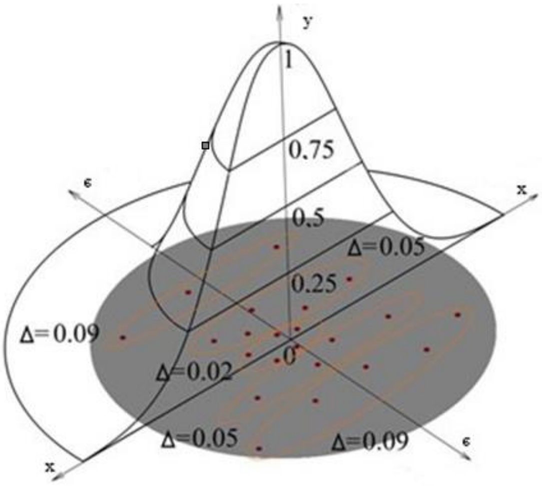

Figure 12. The results of using the new mathematical modeling.

Table 3. The results of analytical calculations and analysis according to the developed method.

	Velocity, V, m/s	Coefficient of Kinematic Viscosity of the Water–Coal Mixture, υ, m^2/s	Maximum Deviation, Δ, m/s	Deviation Standard, σ
Computation1	1.0	350×10^{-6}	0.002	1
Computation2	1.1	354×10^{-6}	0.004	0.9
Computation3	1.12	357×10^{-6}	0.003	0.5
Computation4	1.14	360×10^{-6}	0.003	0.4
Analysis	1.1	348×10^{-6}	0.002	0.9
	The Proportion of Water in the Coal–Water Mixture, W		**Heat of Combustion of Coal–Water Mixture, $Q^{daf}{}_{l}$, MJ/kg**	
Computation5	30		16.2	
Computation6	35		15.3	
Computation7	40		14.1	
Computation8	45		13.2	
Analysis	36.7		15.12	

4. Results and Discussion

4.1. Results

We present the results of the studies of coal and the water–coal mixture in the form of Table 3.

As Table 3 and Figure 8 show, the discrepancy between the values is in the range of 4–5%, which corresponds to the value taken at the beginning of the calculation.

Table 4 shows the results of using a new approximation method when processing measurement results.

Table 4. Results of direct measurements and selections.

	Ash Content of Fuel, A^{daf}	Moisture Content, W^{daf}	Maximum Deviation According to the Measurement Results, Δ, %
Computation1	14.0	34	0.08
Computation2	14.6	34	0.08
Computation3	14.9	33	0.06
Computation4	15.3	33	0.07
Analysis1	15.7	32	0.06
Analysis2	16.2	32	0.07
Analysis3	16.6	31	0.06
Analysis4	17.0	31	0.06

4.2. Discussion

4.2.1. Application of Mathematical Combustion Models for the Design of Thermal Power Equipment

The construction and development of the Bishkek CHP plant began with the equipping of BKZ-160 boilers. The boiler installation project was carried out with minimization of fuel supply and dust preparation costs, and even the mill reserve is excluded. In the furnace, the number of screen pipes for burners installed in one tier is reduced as much as possible. Each burner has two dust channels with dust supply from various mills (Figure 13a,b).

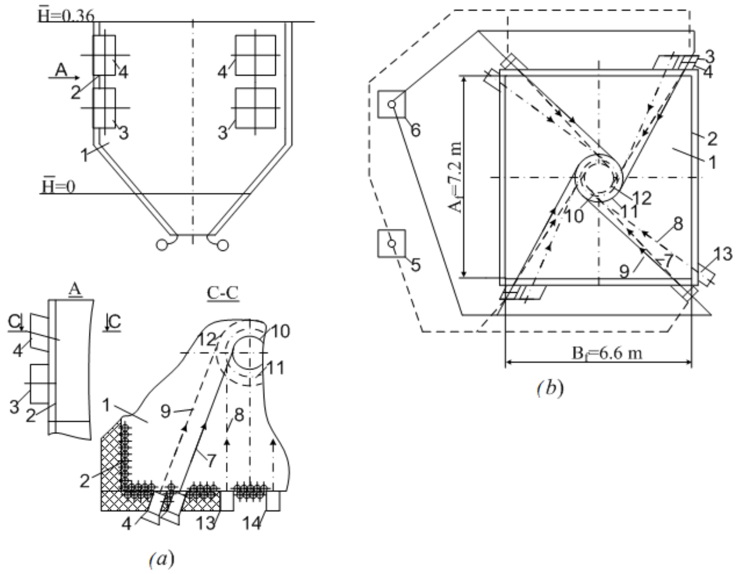

Figure 13. The scheme of the boiler furnace BKZ-160: (**a**,**b**) longitudinal and transverse sections of the active combustion zone of the furnace with existing dust ducts and multifunctional burners on the side walls; 1—the active combustion zone of the furnace; 2—screens; 3, 4—burners of the lower and upper tiers; 5, 6—mills; 7, 8, 9—flows of dust–air mixture, natural gas, air; 10, 11, 12—conditional contact circles of reagents 7, 8, 9; 13—gas nozzles; 14—fuel oil nozzles; $\overline{\mathrm{H}} = \mathrm{H}/\mathrm{H}_\mathrm{T}$, where H and H_T—current and full height of the furnace, m.

The temperature level of the torch at the end of the active combustion zone is also overestimated on $\Delta T \geq 100$ K. Under these conditions, even when working on project fuel, fuel rock particles began to melt, screens and a cold funnel were slagged, and slag removal augers were clogged with slag. Boilers were stopped in an emergency order for slacking. In order to improve the combustion process on boilers, a low-cost reconstruction of combustion systems was carried out with the organization of dispersed input of reagent flows into the active combustion zones. This caused a change in the nature of burning dust project coal with a decrease in the temperature level of the torch, including at the end of the active combustion zone.

Additionally, the slagless load can be increased when switching to low-temperature fuel combustion. To achieve this, it is proposed to preserve the supply-diffusion mechanism already implemented on boilers for feeding the torch with an oxidizer with separate (dispersed) input of reagent flows into the furnace. However, it is advisable to switch to specially designed multifunctional burner devices. The experience of such burners shows that ultra-low values of falling heat flows are formed in the direction of the embrasures. This increases their durability with the extension of the repair period to 12–16 years or more. In a low-temperature flare, the activity of oxidative processes, the formation, in particular, of nitrogen oxides, decreases. The concentration of this substance harmful to human health and the environment in the exhaust combustion products is lower than with conventional dust combustion.

4.2.2. Use of Coal–Water Slurry for Combustion

A coal–water slurry is a mixture of coal dust and water with or without additives of surfactants, having fluid properties, which is able to move through pipelines using pumps, spray into droplets in furnaces, and burn with the formation of a torch, which makes it similar to fuel oil, diesel fuel, and other fuel liquids.

The authors note that reducing emissions of CO_2 is associated with a decrease in the proportion of coal in the water–coal suspension and an increase in the proportion of water. However, there is a limitation on the heat of combustion. At a certain heat of combustion, the use of coal–water suspension becomes economically unprofitable. Therefore, it should be emphasized that the determination of the most favorable fuel and water ratios can be performed only for specific conditions of fuel combustion and its transportation to the place of combustion.

Hydraulic calculation of the pressure transportation system is usually performed at a given capacity in accordance with the solid, known qualitative characteristics of the transported material and hydraulic mixture and consists in calculating and selecting the most appropriate concentration, favorable regime, pipeline diameter and calculating specific pressure losses for friction.

Within the framework of economic efficiency and hydraulic transport, the concentration should be considered approximately to the maximum saturation of the hydraulic mixture. In fact, in hydraulic transport flows, the greatest saturation can be presented in such a way that sufficient mobility and hydrodynamic stability of the flow remain to ensure its transport capacity at an acceptable optimal energy intensity of the process, i.e. when free, economically useful transfer of the solid phase by the liquid transport flow under pressure is provided.

Experimental data obtained by various researchers and scientific institutions during the transportation of coal hydraulic mixtures consisting of coal with a grain size of 0–3, . . . , 0–1 mm and finely ground particles, the maximum saturation of the hydraulic mixture, depending on the qualitative characteristics of the transported material, is a concentration equal to 55-62% by weight. In the case of such a saturated change in the flow structure, hydraulic mixtures can sometimes obtain abnormal non-Newtonian properties. In this regard, based on the conditions of safe operation of the hydraulic transport system, the working concentration of the coal mixture should be taken less than the limit.

For the type of hydraulic mixture under consideration, composed of finely ground Karakechinsky brown coal, the optimal value of the mass concentration can be assumed to be equal to $C_{opt} = 0.9C_{pos}$, where C_{pos} is the maximum possible mass concentration of the hydraulic mixture for this material, in percent or fractions of a unit, and C_{opt} is the optimal mass concentration of the hydraulic mixture, ensuring reliable (without clogging) transportation of the hydraulic mixture, in percent or fractions of a unit.

Experimental studies of the parameters of hydrotransport of Karakechinsky coal were carried out on stands whose pipelines differed from hydraulically smooth ones.

The change in the roughness of pipelines significantly affects the magnitude of hydraulic resistances during the movement of water and hydraulic mixture.

Therefore, when designing hydraulic transport systems, it is advisable to calculate the specific friction pressure losses for hydraulic transport conditions in hydraulically smooth pipes. In this regard, the experimental data obtained were given, and subsequent calculations and forecasting were performed for the conditions of hydraulically smooth pipelines.

5. Conclusions

The field of direct application of CWS in the energy sector is thermal power plants and boiler houses located in areas where, for various reasons, there is no possibility of building access railways or dry coal conveyor delivery systems, and there are no sites for receiving and storing solid fuel. In addition, it can be thermal power plants that receive lump coal in the water flow through a pipeline with the separation of large fractions and their supply to the traditional dust preparation system, and the settled sludge residue into the nozzles of boilers for flare disposal. It is also possible to flare the disposal of CWS from waste oil and oil products with the inclusion of solid coal particles at the power boilers of thermal power plants and industrial enterprises. The first two cases, based on the complexity of the delivery of coal lying in the mountainous areas, are quite adequate to the conditions of the Republic of Kyrgyzstan.

1. The authors presented the results of experimental studies of the thermophysical properties of coal and a coal–water mixture. With respect to the coal–water mixture, its movement through pipelines and combustion were considered. The results obtained were compared with the results of calculations using a mathematical model and the results of numerical modeling in Ansys.
2. New methods of approximation of step functions were used for the mathematical model of error estimation. These methods make it possible to reduce errors in the approximation of the functions of the thermal properties of coal, in particular, in determining the coefficient of kinematic viscosity, ash content, and humidity by approximating the obtained data, and the use of new mathematical methods reduces the error in calculations.
3. Data on numerical modeling of hydraulic transport and combustion processes are presented, and a data validation procedure is carried out. The data convergence shown and their location in the selected band of uncertainties satisfy the requirements for verification of experimental data adopted in the European Union and in the Eurasian Union.

Author Contributions: Conceptualization, K.O. and S.A.; Data curation, K.O.; Formal analysis, K.O.; Investigation, K.O.; Methodology, K.O.; Project administration, K.O.; Supervision, K.O. and S.A.; Validation, K.O. and S.A.; Visualization, K.O. and S.A.; Writing—original draft, K.O. and S.A.; Writing—review & editing, K.O. and S.A. All authors have read and agreed to the published version of the manuscript.

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Nomenclature

ρ_{mix}	density of coal–water mixture, kg/m^3;
υ	kinematic viscosity coefficient, m^2/s;
c_p	heat capacity of the water–coal mixture, J/(kg K);
D	pipeline diameter, m;
V	the speed of the water–coal mixture, m/s;
i_{mix}	specific pressure losses during the movement of the hydraulic mixture (experimental data);
i_{wat}	specific pressure losses during water movement (experimental data);
i_{mid}	middle specific pressure losses during water movement (calculated data);
λ_s	hydraulic friction coefficient for hydraulically smooth pipelines;
$Q^{daf}{}_{l\,theor}$	heat of combustion of freshly extracted coal, MJ/kg;
$Q^{daf}{}_{l\,real}$	heat of combustion of coal delivered to the Bishkek CHP warehouse, MJ/kg;
lf	torch length, m;
Tf	torch temperature, K;
A^{daf}	ash content of fuel, %;
W^{daf}	fuel humidity, %;
V^{daf}	the output of volatile combustible substances of fuel, %.

References

1. Zhang, Y.; Xu, Z.; Liu, D.; Chen, Y.; Zhao, W.; Ren, G. The influence of water occurrences in CWSs made of lignite and bituminous coal on slurrying performances. *Powder Technol.* **2022**, *398*, 117150. [CrossRef]
2. Ahamed, M.; Perera, M.; Matthai, S.; Ranjith, P.; Dong-Yin, L. Coal composition and structural variation with rank and its influence on the coal-moisture interactions under coal seam temperature conditions—A review article. *J. Pet. Sci. Eng.* **2019**, *180*, 901–917. [CrossRef]
3. Chai, Z.; Ren, Y.; Zhang, R.; Feng, L.; Liu, S.; Wang, Z.; Zeng, M. Stability and settling performance of coal water slurries under vibration conditions. *Powder Technol.* **2020**, *376*, 351–362. [CrossRef]
4. Chai, Z.; Zeng, M.; Ren, Y.; Zhang, R.; Feng, L.; Zhao, Z. Prediction method on the static stability of a coal water mixture. *Energy Fuels* **2019**, *33*, 3998–4008. [CrossRef]
5. Kuznetsov, G.; Vershinina, K.; Valiullin, T.; Strizhak, P. Differences in ignition and combustion characteristics of waste-derived oil-water emulsions and coal-water slurries containing petrochemicals. *Fuel Process. Technol.* **2018**, *179*, 407–421. [CrossRef]
6. Liu, S.; Zhang, D.; Lun, Z.; Zhao, C.; Wang, H. Occurrence of water within different rank coals: A review. *Energy Sources Part A Recover. Util. Environ. Eff.* **2020**, *A*, 1–19. [CrossRef]
7. Wang, J.; Chen, J.; Liu, J.; Liu, H.; Wang, M.; Cheng, J. Synergistic effects of mixing waste activated carbon and coal in co-slurrying and CO2 co-gasification. *Powder Technol.* **2021**, *395*, 883–892. [CrossRef]
8. Wang, J.; Liu, J.; Wang, S.; Cheng, J. Slurrying Property and Mechanism of Coal–Coal Gasification Wastewater–Slurry. *Energy Fuels* **2018**, *32*, 4833–4840. [CrossRef]
9. Keboletse, K.P.; Ntuli, F.; Oladijo, O.P. Influence of coal properties on coal conversion processes-coal carbonization, carbon fiber production, gasification and liquefaction technologies: A review. *Int. J. Coal Sci. Technol.* **2021**, *8*, 817–843. [CrossRef]
10. Liu, S.; Zhao, H.; Fan, T.; Zhou, J.; Liu, X.; Li, Y.; Zhao, G.; Wang, Y.; Zeng, M. Investigation on chemical structure and hydrocarbon generation potential of lignite in the different pretreatment process. *Fuel* **2021**, *291*, 120205. [CrossRef]
11. Li, L.; Tong, S.; Duan, L.; Zhao, C.; Shi, Z. Effect of CO_2 and H_2O on lignite char structure and reactivity in a fluidized bed reactor. *Fuel Process. Technol.* **2020**, *211*, 106564. [CrossRef]
12. Zhao, Z.; Zhang, T.; Li, X.; Zhang, L.; Zhang, Z.; Chen, Y.; Wu, F.; Luo, C.; Zheng, C. NO formation mechanism of CH_4/NH_3 jet flames in hot co-flow under MILD-oxy condition: Effects of co-flow CO_2 and H_2O. *Fuel* **2021**, *313*, 123030. [CrossRef]
13. Noble, A.; Luttrell, G.H. A review of state-of-the-art processing operations in coal preparation. *Int. J. Min. Sci. Tech.* **2015**, *25*, 511–521. [CrossRef]
14. Peng, L.; Wang, Z.; Ma, W.; Chen, X.; Zhao, Y.; Liu, C. Dynamic influence of screening coals on a vibrating screen. *Fuel* **2018**, *216*, 484–493. [CrossRef]
15. Osintsev, K.; Aliukov, S.; Kuskarbekova, S. Investigation of Operation of Coil-Flow Steam Generator of Serpentine Type in Conditions of Low Ambient Temperatures. *Int. J. Heat Technol.* **2021**, *39*, 1164–1172. [CrossRef]
16. Osintsev, K.; Aliukov, S.; Prikhodko, Y. Management of the Torch Structure with the New Methodological Approaches to Regulation Based on Neural Network Algorithms. *Energies* **2021**, *14*, 1909. [CrossRef]
17. Osintsev, K.V. Studying flame combustion of coal-water slurries in the furnaces of power-generating boilers. *Therm. Eng.* **2012**, *59*, 439–445. [CrossRef]
18. Melzer, D. On the expressibility of piecewise-linear continuous functions as the difference of two piecewise-linear convex functions. In *Quasidifferential Calculus*; Demyanov, V.F., Dixon, L.C.W., Eds.; Springer: Berlin/Heidelberg, Germany, 1986; pp. 118–134. [CrossRef]
19. Alyukov, S.V. Approximation of step functions in problems of mathematical modeling. *Math. Model. Comput. Simulations* **2011**, *3*, 661–669. [CrossRef]
20. Zhiltsov Yu, V.; Elshin, V.V. *Modeling of the Process of Burning Pulverized Coal Fuel in the bkz-500 Power Boiler Using the Ansys Fluent Software Package, Modern Technologies. System Analysis. Modeling no. 4*; Irkutsk State University of Railway Transport: Irkutsk, Russia, 2016; pp. 150–154.
21. Williams, F.A. *Combustion Theory*; Westview Press: Boulder, CO, USA, 1985.
22. Spalding, D.B. *Some Fundamentals of Combustion*; Butterworth's Academic Press: London, UK, 1955.
23. Ponomarev, V.B. *Calculation and Design of Equipment for Air Separation of Bulk Materials*; Publishing House Ural University: Yekaterinburg, Russia, 2017.
24. Pomerantsev, V.V.; Arefyev, K.M.; Akhmedov, D.B. *Fundamentals of the Practical Theory of Combustion*; Energoatomizdat: Leningrad, Russia, 1986.
25. Barsky, M.D. *Fractionation of Powders*; Nedra: Moscow, Russia, 1980.
26. Chernetsky, M.Y.; Gavrilov, A.A.; Dekterev, A.A.; Surzhikova, N.S. A modified mathematical model for calculating the flare burning of micro-mill coals. *Therm. Fund. Energy Tech.* **2009**, *1*, 159–166.
27. Burdukov, P.A.; Popov, V.I.; Chernetskiy, M.Y.; Dekterev, A.; Hanjalić, K. Autothermal combustion of mechanically-activated micronized coal in a 5 MW pilot-scale combustor. *Fuel* **2014**, *122*, 103–111. [CrossRef]
28. Mandø, M.; Rosendahl, L.; Yin, C.; Sørensen, H. Pulverized straw combustion in a low-NOx multifuel burner: Modeling the transition from coal to straw. *Fuel* **2010**, *89*, 3051–3062. [CrossRef]
29. Asotani, T.; Yamashita, T.; Tominaga, H.; Uesugi, Y.; Itaya, Y.; Mori, S. Prediction of ignition behavior in a tangentially fired pulverized coal boiler using CFD. *Fuel* **2008**, *87*, 482–490. [CrossRef]