

PROSPECTS FOR USE OF MICRONIZED COAL IN POWER INDUSTRY

by

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Heat-and-power engineering is the basis for industrial development of developed countries and the main energy fuel for plants is coal. The main directions in improvement of coal energy technologies are related with better ignition of powdered fuel and with gas and mazut substitution with coal powder. This paper considered the prospects of energy coal enrichment and the method for production of ultrafine coal with the average size of particles about 10–20 microns, and the existing machines for ultrafine coal production. This method increases substantially the velocity of ignition and combustion of pulverized coal flame. The changes of physical and chemical properties of coal after grinding were considered, the processes of ignition, combustion of micronized coal, spaying and stabilization of flame combustion were analyzed in this paper. The problem of ultrafine coal ignition were considered also.

Introduction

Coal is the main energy fuel now; the deposits of coal are many times higher than for any other organic kind of fuel. At the planned rates of growth, the coal energetics will be capable to provide humankind with energy and heat for at least 500 years.

Now in industrial countries (USA and others), coal is the main kind of fuel. Therefore the problem of improvement and development of new power technologies for coal became a crucial task. Besides modern technologies with gas-steam plants working on coal (they use the super-high steam parameters – $P \sim 300$ bar, $t = 650-700$ °C), the problem of effective and "environmentally friendship" combustion of coal-dust fuel remains a pressing problem, because now the most part of coal is burned on power plants in the form of pulverized coal. These days we have a topical problem of gas and mazut (heavy oil) substitution with coal-dust fuel; this is caused by a decline in gas and oil production and use of sophisticated petroleum refinery technologies. This problem is urgent both for major power plants (for ignition and "highlighting" of a coal-dust flame),

and for local industrial power plants, consuming up to 35% of power-plant fuel. This paper considers the problem of using the ultra-fine grinding coal at plants of "big" and "small" energetics, especially for ignition and sustaining of a coal-dust flame. First of all, let us consider the methods of coal preparation for power plant needs.

Prospects for coal enrichment in power industry

The current ecological and economical situation necessitates a reconsideration of requirements to coal for power plants and new scientific grounds for approaches in fuel enrichment problem applicable in coal energetics.

The coal supplied to power stations without enrichment has the raw coal ash at the level 28–33%, but the ash content in enriched coal, which is common in industrial countries like the USA, Germany, UK, Australia, is kept at the level of 5.5–15%. Perspectives of coal enrichment are illustrated by this fact: every additional percent of ash reduces the plant power and requires the additional 0.5 g of solid-equivalent-fuel per 1 kW and increases the mazut consumption by 1.5%, and causes some other negative outcomes.

Analyzing experience of industrial countries, we can list the following environmental factors favoring the fuel enrichment: the loss of land for dumps of ash and slag is smaller, and air contamination with emissions of sulfur and nitrogen oxides becomes lower (depending on the organic and mineral composition of the coal).

If we take the solid fuel with grain larger than 6 mm, then the up-to-date experience of concentrating mills for coking of coal can be applied. But for small-grain coal, the concentrating procedure has some peculiarities, and many processes require new technologies and apparatuses to meet the modern world level.

One of the complex problems is a reduction of ash in the coal with the size about 1mm, and the universal method for coal enrichment is floatation. The methods of flocculation 1 were developed for enrichment of the fine fraction (0.2 mm). This method of floatation can be implemented effectively on a flotator.

We should highlight the wide opportunities of floatation for removal of sulfur from coal (sulfur is represented in form of sulfide minerals – pyrite and marcasite 2, 3). Removal of sulfur in sulfate and elementary forms is a more difficult task, and organic sulfur can be removed only by chemical or biological methods.

The Institute of Solid Fuel Enrichment (Russian Ministry of Fuel and Energy) developed a conceptual scheme of coal concentration for power plants (see the diagram in Fig. 1 4).

The raw coal is exposed to selective fragmentation and then fed to the screening drum 1 for removal of large rocks. The sieved product is supplied to the screening that produces a big, middle, and fine fraction, and the screening 2 as well. The size of screening depends on the character and size of ash-forming components (minerals) and can be less than 6, 3, and 1 mm, that is, the dissemination of minerals in organic mass determine the grinding size with the purpose to open the organics-mineral aggregates.

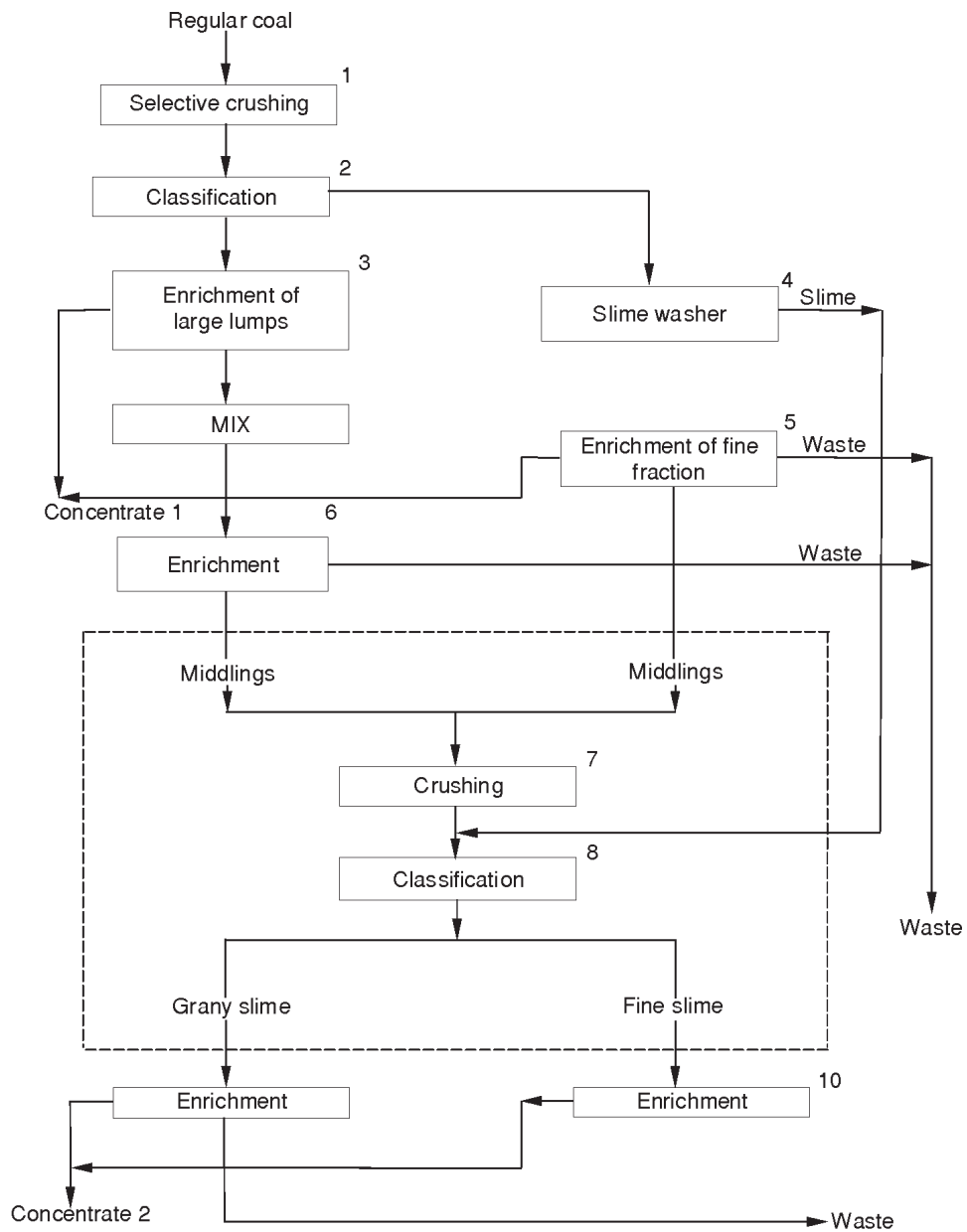


Figure 1. Conceptual scheme of deep enrichment of coal for power plants

Enrichment of big grades produces concentrates with low ash: this became possible to a sophisticated level of concentration technology in heavy media and jigging. The new aspect in this scheme is enrichment of a mixture of intermediate product and waste 6.

The completeness of fuel extraction depends on structure of the intermediate product, which usually has to be subjected to additional fragmentation and second enrichment 7. The efficacy of these stages (fragmentation 7 and enrichment 9, 10) depends on the nature of coal mineralization.

The screenings after stratification on narrow classes (0.5...1.0; 0.25...0.5; 0.25...0 mm) are fed for enrichment: gravitational enrichment is applied for the fraction of material with then size bigger than 0.5 mm, and floatation (the foam and flocculation flotation) suit for fraction 0.5 mm. Concentrate 2, if it meet the requirements on detrimental impurities, can be used for combustion and also considered as a new kind of fuel – a water-coal suspension (WCS).

In general, feasibility of a specific kind of coal enrichment can be found through technical-economic analysis.

Fine and ultrafine grinding of coal as a method of controlled change of physical and chemical properties

The most applications of coal are related with use of well-milled coal, and the grinding level is determined by the specific chemical-technological treatment. It is known that with a higher degree of fineness and the value of specific surface ΔS , the surface energy ΔG_{surf} also increases:

$$\Delta G_{surf} = \sigma \Delta S$$

However, at the size below 0.001 mm the coal exhibits some new features, quite different from the properties of same coal, but larger size. Therefore this sort of coal was named "micronized coal". Several anomalous properties of a "micronized coal" (bitumen yield, for example) could not be explained only by an increase in the specific surface. A more detail study of these properties gave us a basis to consider these structural-chemical changes as a result of a mechanochemical process 5, 6 .

Mills and micronizing apparatuses

The fine dust state for coal is usually obtained in mills with a higher energy stress than regular drum-mill facilities: these are the vibrating, jet, and planetary-motion mills, and also special grinding apparatuses (disintegrators are the most wide-spread facilities).

However, even in drum mills, where grinding is achieved from the gravitational force of balls, a fine grinding is available after a long run.

Wide-spread vibrating mills are designed for fine grinding, and grinding performance is determined by number of vibrations of a drum (and amplitude), grinding time, and other technological parameters.

The efficiency of vibration mills has a convenient characteristic

$$\Phi = \frac{\alpha\omega^2}{g} \quad k\alpha\eta^2 \quad (1)$$

where Φ is the repetition factor for circular oscillation acceleration (centrifugal factor), often expressed as a fraction of gravity force.

Industrial vibromills have the value of about 12–16 at the amplitude 4...6 mm and the power consumption (0.8...1.2) 10^{-3} kWh/cm³ in the chamber volume. Nowadays the machines have been developed with (key factor of energy impact) by several times higher. This kind of machines - vibrocentrifugal mills (named so because the motion trajectory is close to circular) – might be a promising device for production of micronized coal. The example can be a three-sectional vibrating mill designed in the Institute of Solid State Chemistry and Mechanochemistry SB RAS 7 . This kind of mills can regulate the shock-and-grinding regime of treatment and provide a proper level of fineness and structural changes in the mineral substance.

In jet mills, the grinding is achieved due to particle collision at the opposing motion with high velocities (100 m/s and higher) in gaseous flows. The main advantage of this technique is the opportunity to obtain fine and ultra-fine (less than micron) particles; and the outcome size is controllable 8, 9 . The jet mills with capacity from 1 kg/h up to several tons per hour can be manufactured.

A disintegrator is an apparatus of shock impact operating in a flow regime. The design of this machine usually comprises of two drums with opposite rotation. The disk of every drum has several beaters (rings) over the circumference. Grinding is the result of multiple collisions with beaters, and it is proportional to the strength and velocity of collision. Industrial disintegrators with capacity 20...30 tons/hour were constructed 10, 11 .

Planetary mills

Since 70s, more than 30 constructions of this type of grinder have been developed. Its main advantages are a high degree and rate of milling, because the critical rpm is higher than for drum mills. Since the size and mass of the setup is reasonable, this mill can be installed on small grounds [5].

The operational principle of a planetary mill is as follows (see Fig. 2). The mill drum with the radius of R_2 participates in two rotations: around the general axis O with radius R_1 and angular velocity ω_1 and revolution around the drum axis O_1 with angular velocity ω_2 . With this approach, a barrier of the critical rotation number is overcome and high centrifugal acceleration is attained.

The kinematic parameter is the ratio

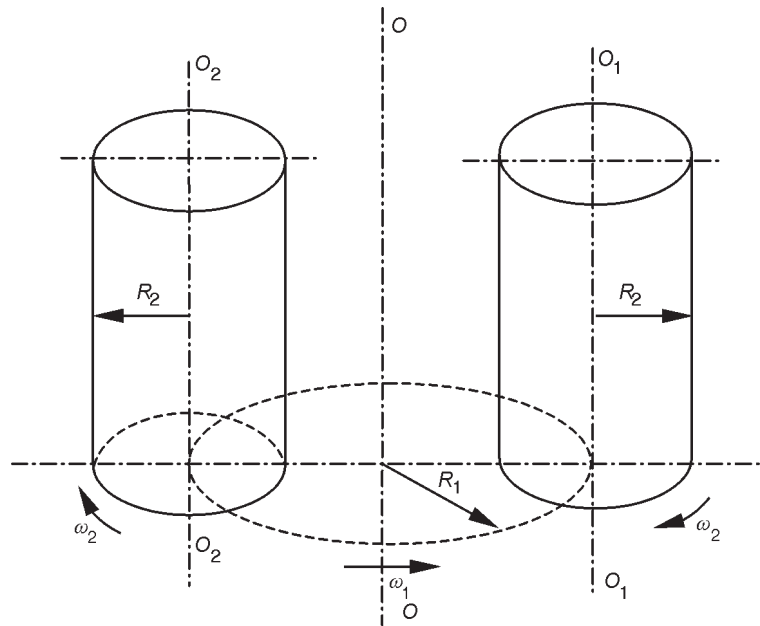


Figure 2. Diagram of planetary mill

$$K = \pm\omega_2/\omega_1,$$

The geometry index is

$$m = R_2/R_1,$$

The process of disintegration for solid bodies occurs under action of high centrifugal forces, determined by energy stress of the mill. The approximate formula for the energy stress factor is the following:

$$X = \frac{\omega_1^2 R_1}{g} + \frac{\omega_2^2 R_2}{g} = \frac{\omega_1^2 R_1 (1 + K^2 m)}{g} \quad (2)$$

where X is the ratio of the sum of accelerations of type of motion in planetary regime to the gravity acceleration. The sample of laboratory mills with X about 100 and even 200 were created.

The planetary mills are used widely for fine grinding of coal for study of its physical and chemical characteristics in a micronized state.

Physical-chemical alterations of coal after fine and ultrafine grinding

For fine grinding of coal, two processes are typical: milling with growth of the specific surface S and aggregation of these fine particles after a long time of grinding, which acts the opposite and reduces the value of S . This process is accompanied by a drastic growth of coal reactivity in different processes and chemical reactions. Fine grinding is accompanied by a growth in the external and intrinsic surface due to opening of pores being closed previously, and due to formation of new pores caused by formation of microcracks in coal. The volume of micro- and moderate-size pores increases by several times, so we may tell about a drastic change of initial structure of porosity.

We should note a slowdown in refinement after the size 2...10 microns has been achieved. This is explained by particle reinforcement after partial opening of micro- and meso-pores. The deeper refinement requires a higher energy stress of the grinding process.

Table 1. Chemical and technological characteristics of coal after fine grinding

Coal	Medium for grinding	Grinding time	Parameters							
			Specific surface, S m ² /g	W^a , %	A^c , %	V_c , %	Carboxy-groups mg-eq/100 g	G^r , %	H^r , %	N + O, %
Z	Air	Initial	3.2	2.95	6.20	32.90	244.4	81.42	4.83	13.75
		5	9.7	2.10	6.00	31.70	309.5	80.55	4.79	14.67
		15	8.0	2.40	6.70	31.70	314.4	80.85	4.73	14.42
	Water	5	9.2	3.10	7.50	32.70	267.6	81.53	5.08	13.39
		15	13.0	3.40	10.50	31.90	269.2	81.72	5.08	13.20
		Initial	1.95	1.25	3.10	8.40	47.1	90.83	3.56	5.61
T	Air	5	57.3	1.65	3.50	11.10	65.8	89.73	3.50	6.77
		15	223.0	1.55	4.00	13.80	164.3	87.25	3.47	9.28
		5	7.5	1.40	4.50	9.30	11.9	91.39	3.68	4.94
	Water	15	20.0	1.35	6.20	10.10	8.1	91.15	3.78	5.07
		Initial	1.95	1.25	3.10	8.40	47.1	90.83	3.56	5.61
		5	57.3	1.65	3.50	11.10	65.8	89.73	3.50	6.77

Another aspect, causing alternation of many properties, are X-ray-detected structural changes directed to a decrease in structural order. One can see in diffractograms a widening of lines and new scattering background; the reflex maximum intensity diminishes. All of that is a manifestation of a deep breakdown of the fine structure of coal substance caused by plastic deformation.

The important fact is that the density decreases from 1.59 down to 1.39 g/cm³: a loosening of structure takes place due to breakage of chemical bonds and restructuring of a macromolecule.

The degree and character of alteration in coal composition and properties depends on the metamorphism of the sample, ambient medium, and technological

parameters of grinding. The Table gives chemical and technological characteristics for two ranks of coal from Kuzbass deposit, after coal micronizing. After grinding for 15 minutes, the value of S for rank Z rises up to $13 \text{ m}^2/\text{g}$, and for rank T – up to $200 \text{ m}^2/\text{g}$. Moreover, this anomalous high level of S was achieved after dry grinding, but wet grinding increases S only to level $20 \text{ m}^2/\text{g}$. One can assume that treating of T-coal in air produces a more intensive crack-formation, and so this yields a high specific surface.

While mechanical processing in mills, local concentrations of mechanical and heat energy are produced, causing a breakage in chemical bonds. Although the level of excitation impulses are less than the energy of chemical bonds, still a breach of bonds is still possible with a repetitive impact with the energy of $10 \dots 100 \text{ kcal/mol}$, what is not more than 20% of the chemical bond energy.

A tearing off lateral chains with formation of free radicals is most possible for molecules of coal. This radical-forming way of decay was well studied by the method of electronic paramagnetic resonance (EPR). Free radicals are generated in coal due to breach of C-C bonds, and the unpaired electron belongs both to the first and second atoms of carbon. For high-carbon materials, the concentration of paramagnetic centers is up to $10^{17} \text{--} 10^{19}$ per gram. It is exactly the free-radical formation, which is responsible for a high chemical activity of coal, including inclination to oxidation and combustion.

Coal grinding in oxidizing medium (in air atmosphere) causes an increase in content of primary and secondary alcohols, phenol hydroxides and CH-aromatic groups. If the medium is inert, this facilitates the formation of carbonyl groups, *i. e.*, the situation of a hydrogen medium is reproduced.

The general trend in transforming of organic substance is formation of products with low organic mass. This must be the reason for a higher reactivity.

All the consequences of activation through grinding open wide opportunities for application of this method in different areas where coal is used.

Analysis of ignition and combustion of coal suspension

Combustion of a natural solid fuel is a complex physical-chemical process governed by a series of aerodynamic, thermal, and chemical phenomena: conditions of particle streamlining by gas medium (determine the convective mass and heat transfer), temperatures in flow and on chamber walls (they control heating of the particle, moisture evaporation, extraction and ignition of volatile components, coke residue burning, physical-chemical transformations of the mineral components, *etc.*). All of these processes go either in parallel or consequently, the reaction sequence and chemical constants can be changed, with possible switch-on of a chain mechanism.

Therefore, the complete analysis of all processes is hardly possible even with use of modern computer facilities. Thus, it is reasonable to consider these processes stage-by-stage with analysis of separate processes and with putting of them into a general scheme.

Since a coal-dust flow consists of small particles with a high distance between them, the analysis of ignition and burning of a single particle is of great interest. Usually

first approximation for analysis of coal-dust flame is analysis of a single spherical particle. It is assumed also [12–14] that the stages of drying, release and combustion of volatiles and coke residue occur step-by-step. It is assumed that the time for water vapor release and the most fractions of volatiles is determined by the heat-up time for the particle. The ash content (at moderate levels) does not influence the burn-out time for the coke residue. The effect of reaction inside the pores is usually negligible for regular range of furnace temperatures.

Since the size of dust-coal particles is small ($d_{av} = 50\text{--}70$ microns), they are taken away by gas flow. Therefore one can assume that all the surface of the reacting particle is equally accessible for a diffusing oxidizer, *i. e.*, the diffusion number of Nusselt $Nu_d \approx \beta d/D = 2$, where β is the coefficient of mass transfer, D is the diffusion coefficient for oxidizer, and d is the particle diameter. For the most simple case of ten first-order reaction, the total rate of reaction of a coal particle (according to the diffusive-kinetic theory of fuel combustion) is

$$q = KC_{\omega} \frac{kC_0}{1 + \frac{k}{\beta}} \frac{C_0}{1 + \frac{1}{\beta}}$$

and the total resistance to fuel transport toward the particle is $1/K' = 1/K + 1/\beta = 1/K + d/NuD$. It consists of the chemical $1/K$ and d/NuD diffusive terms of resistance.

According to modern concepts [12], the particle combustion in a coal-dust flame at usual furnace temperature occurs predominately in a diffusion mode, *i. e.*, the main resistance to the process is of diffusive nature – d/NuD .

Considering the last simplifying relationship, we see that the diffusive resistance decreases linearly with decreasing particle diameter. Besides, with transition from regular grinding for coal-dust boilers producing the particles with the size of $60\text{--}70 \mu\text{m}$ to the micronized grinding ($d_{av} = 15\text{--}20 \mu\text{m}$) enlarges the entire reactive surface by factor of three. Since the diffusive resistance also decreases by the same amount, we expect that the total rate of burn-out in diffusion regime have to increase by 5–7 times.

Since it is widely expected that emanation of volatile components is governed mainly the rate of particle heat-up and proportional to the square of particle diameter [12, 13], the rate of volatile emanation increases also with a decrease in the particle diameter.

In general, a decrease in the particle size down to economically and technologically justified size of the mean-modal value $10\text{--}20 \mu\text{m}$ would allow us to achieve the coal flame ignition and burning with a minimal input of heat at the initial stage of the process.

Accomplishing of the ultra-fine grinding technology gives the foundation for achieving of other perspective tasks in power engineering:

- development of system for ignition and stabilization of coal-dust flame operating without mazut, only with micronized coal, and
- substitution of gas and mazut with micronized coal in boiler units of large- and small-scale power plants.

Ignition and stabilization of a coal-dust flame

Because of the continuous decline in quality of power-plant coal, the global amount of mazut used for ignition and enlightenment of coal-dust boilers increases and ranges up to 50 mln tons annually [15]. The joint burning of coal and mazut decreases the economic efficiency of the boiler (the underburning is higher) and environmental parameters become worse because of emission of oxides of sulfur and vanadium. Besides, a slowdown in Russian oil industry and higher level of oil processing the market may face a shortage of heavy oil fuel, and the resulting price growth faster than for coal fuel.

A serious alternative solution could be use of plasmatrons [15]. The first industrial test with plasma-stabilized flame was performed by Blackburn in the US on a plant with 200 MW power.

In the USSR, the first test was run in 1987, on a boiler TP-170 at the Novosibirsk Power Plant-2. Recently the Russian Federal Agency "United Energy System" established the Center of Plasma-Energy Technologies (Gusinohozersk, Buryatia). The business of this center is installment of plasma setups for ignition and enlightenment on boilers of different capacity and operating with different grades of coal. The Center is the head organization in Russia on development of plasma-energy technologies; now the technology of plasma ignition is the only serious alternative to using of gas and mazut.

However, new economic systems of coal ultrafine grinding are developed now. The MicroFuel Corporation (USA) is engaged in production of equipment for fine grinding. Initially, the micronized coal was produced as a price-competitive fuel substituting gas and mazut on power plants. But now they put emphasize on study of the opportunity to use the micro-coal during the boiler start-up. The work was performed using grinding equipment from MicroFuel Corporation on Duke Power Company Cliffside with a unit 600 MW (North Caroline) [17]. The micro-coal in these tests was a dust with most of particles (80–90%) sized less than 43 microns (325 mesh).

To provide this size of particles, an external centrifugal classifier was used. The boiler start-up was performed without air preheating on "cold" boiler. The grinding mills capacity was 5 ton/hour with energy consumption 22 kWh/ton. The main problems were the following: designing of special burners for micro-coal in a tangential furnace; modification of coal feeding system from the micronizer to burners; matching with existing system of process automation, control of micro-coal feeding to burners, installation of special fans. We should note here that coal feeding to a high distance (dozen meters, as in this scheme), might cause aggregation of particles with formation of clusters with size much bigger than the initial size; this might reduce strongly the efficiency of combustion of micronized coal.

The very first tests in the US were conducted in 1982; it was a trial to find the technology to substitute gas and mazut with water- and mazut-coal suspensions. Since that time it has been proven that micronized coal can be used in commercial technologies. The key points in that are the economic and technological parameters of the grinding system.

Therefore the use of micronized coal in municipal power plants was restricted mainly because of big size of the grinding machines of the first generation. The essential aspects are the energy consumption for grinding and characteristics of fuel obtained – grinding, reactive, ash content and quality of mineral component of coal. All these aspects require a special economic, technological and experimental study.

The micronized coal was used for boiler ignition by company Steinmuller (Germany); they even designed a special kindling burner 18 .

In general, there are two ways for production of micronized coal: separation of fine dust in a regular system of coal grinding or using of special grinding equipment, as it was made in 16 .

The option of fine fraction collection from the coal dust and its supply into a loader for further technological use usually faces the problems of feeding of a packed dust from the loader, explosive hazard of the mixture, and bulkiness of the fine-grain separation system.

The method of special preparation of fine-grinding dust is more reasonable. The fuel, grinded and dried by flue gases, is supplied from the general bunker to individual bunkers of every boiler.

However, the most favorable conditions for dust combustion are achieved when the fine-ground dust can be fed from the grinder directly to the burner, because this keeps a high level of chemical reactivity produced after grinding and we have no any problems connected with storage of fine-size dust.

Both schemes with dust separation and special dust preparation were tested of units with capacity 150 and 350 MW at electric power plant Lunen (Germany) at early 80s.

Similar research is conducted in the USA: according to information from Union Carbon Corporation, the percentage of mazut fuel for ignition from the total fuel consumed in coal power plants amounts to 6%. This means that the problem of substitution of expensive mazut with cheaper coal is a serious problem. Here the research progressed even further: they develop projects of use of micronized coal in "Reburning" systems for suppression of NO_x emission 19 , and even the projects are developing on use of micronized coal as the main fuel in mazut-fed boilers (instead of mazut).

The diagram of the boiler on micronized coal developed for 148 MW plant in Miliken (New York State Electric and Gas Corporation) and for 50 MW plant in Rooter (Eastman Kodak Company) is shown in Fig. 3. In this case the micronized coal covers 30% of the total coal feeding, and its fineness parameter is 80% below 325 mesh (*i. e.*, the particle average size is 20 μm instead of 74 μm for regular boilers). The micronized coal is supplied above the main burners, to the zone of active formation of NO_x. For ultra-fine particles, the surface of active reaction is much larger (almost threefold) than in traditional systems, and the chemical activity is higher. This produces the characteristics of a coal flame almost the same as for burning of pulverized mazut. That is why it is possible to achieve a more complete combustion of coal in a smaller furnace volume, less underburning, and higher efficiency of a boiler with a low outcome of NO_x than for regular coal-dust combustion.

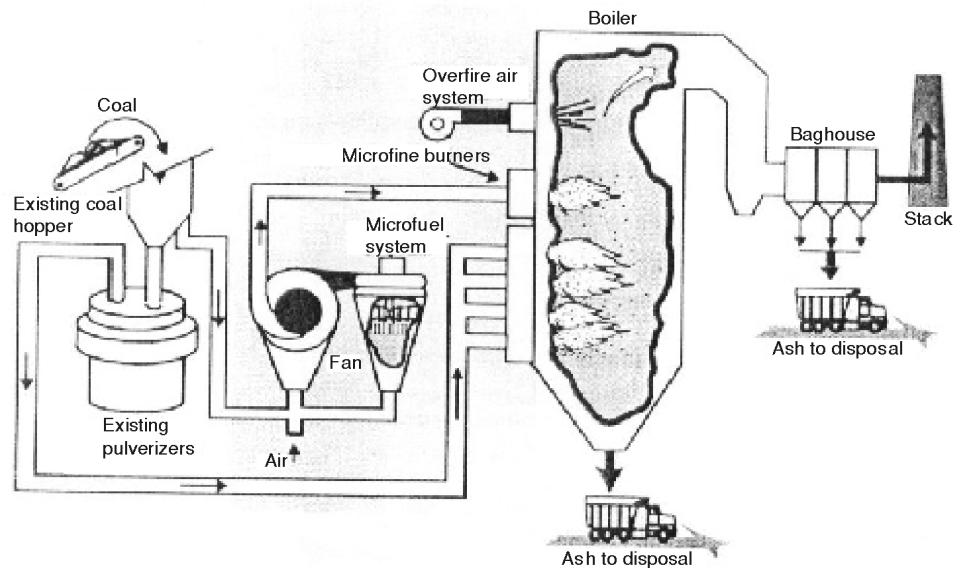


Figure 3. Diagram of a boiler with use of ultra-fine coal for "Reburning"

The main advantages of combustion of micronized coal: the length of flame is by 60% less, the double rate of combustion, a higher percentage of heat delivered by radiation, smaller deposition of ash and slag, so the ash-removal system can be smaller, and smaller size for the steam overheater and economizer.

Another application of micronized coal is the usage in layer boilers, in gasification, in a combined cycle of a Diesel engine, and in gas-mazut boilers [20]. The method of production of ultra-fine dust is an essential point. The very first mills for that production were the air and steam machines (50 s), but the energy consumption in them is 5 times higher than in mechanical grinders.

The American project [20] uses mechanical mills with compulsory system of particle separation to prevent transport large pieces to the combustion chamber. The primary rate of air is 10–15% of the total amount required for complete combustion. Since the coal combustion for ultra-fine dust is more efficient, the air excess might be less than 1.2, so the capacity of fans and smoke exhausters must be lower.

In general, the micronized coal may play a significant role in system of ignition and stabilizing of coal-dust boilers. A special aim is retrofitting of gas-and-mazut boilers to combustion of micronized coal: this could solve the problems of industrial power plants connected with shortage and high prices for mazut. Naturally, this implies the necessity of creating of flue gas cleaning system, which not required for regular boilers on gas and mazut.

Recently, a setup for coal combustion study was constructed in the Institute of Thermophysics, and research on combustion of micronized coal of different grades was initiated; here the systems for flue gases cleaning must be also tested. Simultaneously, we consider the problem of application of new mills for ultra-fine grinding with a direct feeding of the produced dust to the furnace. Several issues have to be solved there:

- (1) Study of mechanisms of combustion rate and coal gasification for ultra-fine grinding for samples of different metamorphosis. The goal of laboratory study is to find conditions and limits for designing of technological devices directed to reduction of NO_x emission, ignition and enlightening of coal-dust boilers, and fuel substitution in gas-mazut boilers.
- (2) Pilot and industrial-scale testing on power plants for combustion of micronized coal and testing of flue gas cleaning system.
- (3) Testing of ignition and enlightenment of coal flame with micronized coal in industrial boilers.

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Nomenclature

ΔS m ² /g	– increase of the specific surface of the coal powder
S m ² /g	– specific surface
ΔG_{surf} J	– surface energy
σ J/m ²	– specific surface energy
P	– pressure
t °C	– temperature
α m	– oscillation amplitude
η 1/s ²	– number of drum vibrations
ω 1/s ²	– angular acceleration
g m/s ²	– gravitational acceleration
k	– is the coefficient depending of the system of units
Φ	– repetition factor for circular oscillation acceleration (centrifugal factor)
R_2 m	– radius of the mill drum
R_1 m	– radius of rotation around axis O
ω_1 1/s	– angular velocity of rotation around axis O
ω_2 1/s	– angular velocity of revolution around the drum axis
X	– the ratio of the sum of accelerations of motion in planetary regime to the gravity acceleration
W^a %	– water content in coal
A^c %	– ash content in coal
V_c %	– volatile content in coal

G^r %	– grinding finesse
H^r %	– hydrogen content in coal
N + O %	– nitrogen and oxygen content in coal
$Nu_d \approx \beta d/D$	– coal particle Nusselt number
β m/s	– mass transfer coefficient
D m ² /s	– diffusion coefficient for oxidizer
d m	– particle diameter
K'	– overall constant of chemical reaction
$K = K_0 e^{E/RT}$	– reaction rate constant
E J/kg	– activation energy
R J/kg	– universal gas constant
T K	– temperature
K_0 m/s	– pre-exponent multiplier
C_o kg/m ³	– oxygen concentration at particle surface
C kg/m ³	– oxygen concentration far from particle surface
q kg/m ²	– total reaction rate
d_{av} m	– mean particle diameter

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