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Coal–Water Suspensions in Power Engineering[1]

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Abstract—The problem of utilizing coal–water fuel in power engineering is analyzed, and prospective fields of its application are determined.

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First investigations into coal suspensions were carried out at the Institute of Combustible Minerals (IGI) and Krzhizhanovskii Power Engineering Institute (ENIN) back in the middle of the past century or even earlier [1–4]. It was as early as that a technology was developed for utilizing environment-polluting dispersed coal slurries, which are generated as coal is enriched, hydraulically extracted, and hydraulically transported from a colliery. The highly stable and highly dispersed nature of slack suspensions is a factor that adds considerably to the cost of desiccating them. Burning slack suspensions directly, i.e., without preliminarily desiccating them, in thermal units would help solve the problem of their utilization. It was supposed that this might under certain conditions be more advantageous and more production-friendly than burning the dispersed coal separated from slack suspensions by desiccating and drying them. Feasibility studies of a technology for directly burning coal slurries were carried out under the assumption that the cost of the latter is low compared with the other costs for reprocessing them into a technologically acceptable fuel.

However, none of the proposed technologies for directly burning slack suspensions have proven to be economically feasible; on the other hand, the environmental aspects of the problem have shown themselves to be troubling to society and significant.

A factor that adds difficulty to practical use of slack-like coal suspensions is that they are inhomogeneous in nature, as they may originate from different sources and places, and because they may be kept and stored under different conditions. Projects for directly burning slack-like coal suspensions have not been implemented, and the constructed installations have now been dismantled.

Another technology, which was developed alongside with direct burning of slurries, was that for obtaining fuel suspensions from a standard ordinary coal, specifically, a coal–water fuel (CWF). Unlike coal slurries, the mineralogical composition and properties of an ordinary black coal are standardized and the amount of coal having a specified composition is virtually unlimited. It is therefore less difficult to produce CWF from it. Coal–water fuel was considered an accessible, although inferior, replacement (palliative) for power-generating products of coal hydrogenation. Methods for obtaining hydrocarbon liquids from coal by hydrogenating it are well known. However, none of the existing technologies based on these methods is sufficiently good; the liquid fuels obtained in pilot commercial installations cannot compete in cost with petroleum products.

The cardinal political and economical challenge of the CWF stems from the fact that commercial-scale reserves of coal are much wider and much more uniformly distributed around the globe than are the overall reserves of petroleum and gas; moreover, the former are many times superior to the latter in energy equivalent. Huge deposits of coal are available in Russia, China, the United States, Australia, Canada, the Republic of South Africa, and many other countries. Technologies for producing coal and transporting it for any, especially long, distances are well furnished with machinery and have a clear-cut organizational structure. The use of coal fired as liquid fuel instead of petroleum products with a view toward making industrially developed countries less dependent on supplies of petroleum was therefore deemed a very tempting prospect.

The potential economic efficiency of using coal fuel stems from a relatively low cost of the energy generated by firing it (at thermal power stations): it is approximately equal to \$1.5/MJ for bituminous coal against \$4.5/MW for fuel oil (according to 1997 prices for energy carriers in the United States: fuel oil, \$150/t, and coal, \$30–40/t, at the place of delivery).

The attitudes people in different countries have had to the above problem and the amounts of money allotted in them to development of suspended coal fuels were determined by a concrete state of affairs and the extent to which the demands of customers were met by locally available energy carriers, as well as by the ratio of the costs for energy generated using locally produced and imported coal, petroleum, and gas. The programs developed in all countries to obtain kinds of fuel

[1] This paper is published for purposes of discussion—Eds.

capable of replacing petroleum and gas (not only suspended coal fuel) were aimed at attaining both economic independence and environmental safety.

Coal–water fuel became especially popular as a subject of research in the 1970s. The task was to develop technologies for obtaining a CWF of such quality that it could replace fuel oil in power-generating units at minimum cost. Among the systems developed within the framework of this problem were those for transporting CWF by pipelines over long distances. A technology for using a CWF in internal-combustion engines and instead of coal in gas generators was developed. A considerable volume of work on replacing coal by CWF in heating boiler houses was also accomplished. This was supposed to help reduce the amount of harmful emissions.

The share that fuel oil and gas had in the energy balance of Russia in 2003 was around 70%; its value in the European part of Russia ran to more than 86%. At present, gas accounts for around 61% of the electricity generated. The share of coal in the generation of electricity in Russia is not more than 26%. The need to increase this share in order to reduce that of gas is more than pressing. Another reason why changing fuel oil- and gas-fired thermal power stations and boiler houses over to operation on coal fuel is economically promising is because this will allow a larger amount of highly valuable energy carriers to be exported. It should be pointed out that the domestic prices existing in Russia for energy carriers has a structure that is unfavorable for hydrocarbon fuel being replaced by coal. For example, the price at which ordinary coal having an average heating value of around 17–20 MJ/kg is sold in the medium belt of Russia is 1800 rub/t; the price of fuel oil having an average heating value of 42 MJ/kg is up to 3800 rub/t. Obviously, the replacement of fuel oil by coal is unprofitable.

A problem of great relevance for Russia is that of delivering coal from the Kuznetsk coalfields to the Ural region and to the European part of the country. The formerly rich coal fields in the European part of Russia have become considerably or even completely depleted, or the production of coal is too expensive as a result of coal strata being meager and lying at considerable depths. Transportation of coal from the Kuznetsk coalfields to the central regions of Russia causes its cost to triple. Therefore, it is economically important for Russia, as well as for China and the United States, countries having well-developed networks of railway and water transport, that networks for hydraulic transportation of coal and a technology for obtaining a coal-based vehicle fuel for transport engines be developed in those areas.

Specialists of the IGI, NPO Gidrotruboprovod, and other scientific centers have carried out a considerable volume of work on developing a technology for preparing, transporting, and firing CWF made of different types of ordinary coal. An experimental industrial facility was designed and constructed, which included a terminal for preparing CWF with a design output of 400 000 t/yr, a 262-km-long pipeline, and a terminal for receiving and firing CWF at a thermal power station in Novosibirsk.

Certain experience in using CWF has also been accumulated in some countries, including China and the United States. China ranks first in the world in the amount of coal being produced and consumed (more than 1 billion t/yr); almost the entire power industry uses it as a basic fuel (95%). One of the problems faced by China is the need to deliver coal from where it is produced to where it is consumed. Since coal delivery routes often go across rugged terrains, transportation of water suspensions by pipelines may turn to be the most profitable choice. In addition, China is interested in exporting coal to Japan and other countries in the Pacific Region with very limited fuel resources. Transportation of coal as part of suspension, loading this suspension in tankers, unloading it, and firing it in accordance with the scheme for firing liquid fuel were thought to be economically rational choices. China, jointly with Japan, has for a few years already been developing projects for producing coal suspensions in China and transporting them by tanker to coastal thermal power stations in Japan, at which these suspensions are to be used in conjunction with fuel oil or instead of it. Some of these projects have passed the final stage and implemented on an industrial scale.

The amount of coal produced annually in the United States is around 900 million tons; 85% of this coal is used to generate electricity. Coal-fired thermal power stations account for around 65% of the entire electric energy produced in the United States; the share of nuclear and hydraulic power stations is equal to 25%. The share of electricity generated by firing petroleum products and natural gas at thermal power stations and in diesel-generators is as small as around 10%. The problem area most relevant for the United States is development of coal-based vehicle fuels for transport engines, which consume the main part of the petroleum produced in and imported into the country. As in China, transportation of coal–water suspension to the countries on the Pacific coast by tanker was considered a promising choice. Transportation of coal by pipelines was regarded mainly as an alternative to costly railway transport. Pipelines have already successfully been operating for many years in the United States—through which, however, coal pulp, rather than suspension, is transported. Unlike coal–water suspension, coal pulp is dehydrated at the end terminal; the coal thus obtained is fired in accordance with a coal-dust technology. An experimental pipeline for transporting coal–water suspension has been constructed; however, it was not put into operation, since the owner of the railway running parallel to the pipeline immediately reduced the tariffs for coal transportation. At present, the operation of this pipeline has also been modified to transport coal pulp.

Industrial projects for using CWF in Europe have not hitherto been implemented.

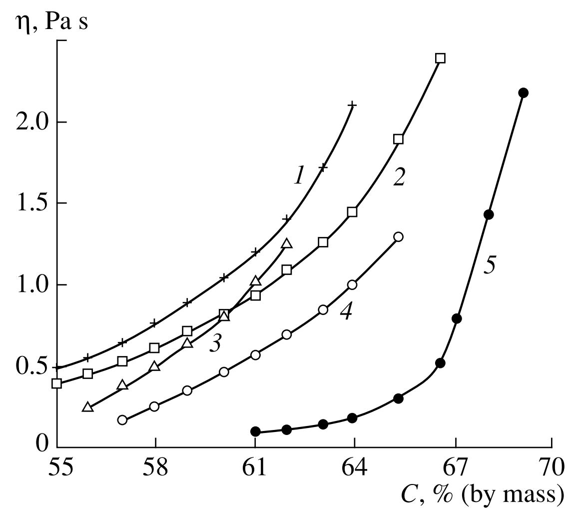

Fig. 1. Effective viscosity of coal–water suspension as a function of coal content (Kuznetsk coalfields, the Inskaya mine and the method of preparation). (*1–3*) From source coal having an ash content of 13.5% [(*1*) according to a single-stage technology without homogenization, (*2*) according to a two-stage technology without homogenization, and (*3*) according to a three-stage technology with homogenization], (*4*) from coal enriched to an ash content of 7% using a two-stage technology with homogenization, and (*5*) from enriched coal having the optimal bimodal granulometric composition.

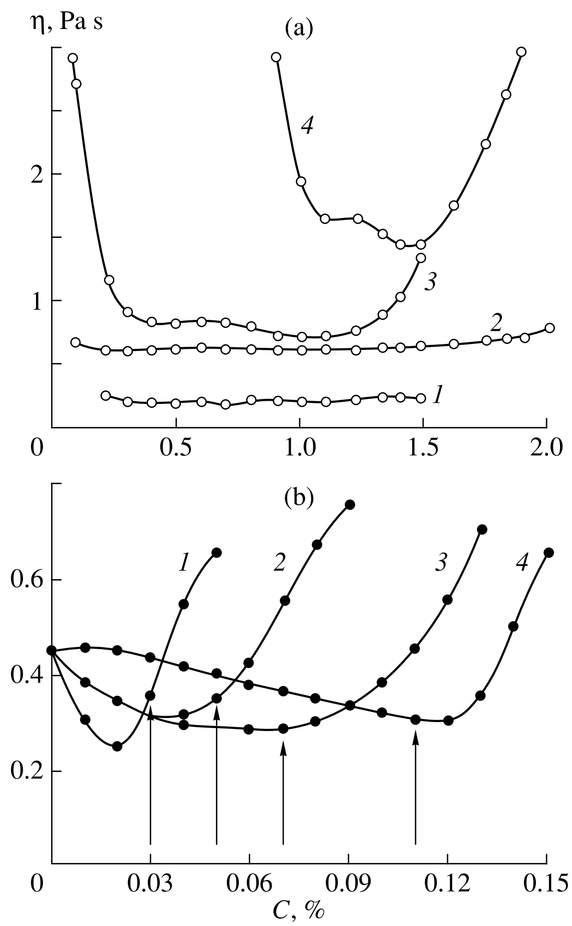

Fig. 2. Effective viscosity of coal-water suspension made of coal composed of two fractions [coarse (c) of 250–125 μm in size and fine (f) of 60–0 μm in size] as a function of the content in it of dispersant (a) and stabilizer (b). Arrows indicate the sedimentation stability threshold. (*1*) Coal content $C = 63\%$, fraction ratio c/f = 60/40; (*2*) $C = 63.5\%$, c/f = 63.4/36.6; (*3*) $C = 66\%$, c/f = 50/50; and (*4*) $C = 63.5\%$, c/f = 66.7/33.3.

MAIN TECHNOLOGICAL CHARACTERISTICS OF FUEL COAL SUSPENSIONS

Technologies for preparing and using petroleum-, methanol-, and water-based coal suspensions have been developed. Coal–water suspensions and CWFs are commonly regarded as the most promising ones. An obvious drawback of coal–water suspensions is that they have a high content of water, the fraction of which is as high as 40% of the composition. It is noteworthy that this indicator cannot be reduced to any appreciable extent, as the viscosity of the suspension increases dramatically with the content of coal (Fig. 1). The way in which the viscosity of coal suspensions depends on the content in them of a solid phase has been studied in detail. This viscosity is influenced by the coal hydrophobicity factor, as well as by the content and composition in it of mineral admixtures in the form of clay. The suspension can be made much less viscous using chemical reagents (surfactants) prepared as a combination of dispersants and stabilizers (Fig. 2), as well as by selecting the granulometric composition of coal particles (Fig. 3). Both these techniques involve considerable expenses, which may account for a considerable part of suspension's cost, commensurable with that of coal.

A high content of water in suspension leads to additional costs for transporting it with coal and then for evaporating it during combustion. Calculations have shown that 1% of coal must be spent for every 10% of water. On the other hand, the advantage a coal–water suspension has over a hydrocarbon fuel is that the former is explosion- and fire-safe at all technological stages of its preparation and transportation. In addition, technologies for preparing coal–water suspensions are well combined with coal enrichment and demineralization processes: coal does not need to be dehydrated upon completion of these processes, which partly compensates for the costs for evaporating the water contained in coal–water suspension and for transporting it with coal.

The use of suspension technologies helps prevent generation of dust and oxidation, phenomena typical of ordinary coal during its transportation and storage. Depending on the conditions, method, and distance to which coal has to be delivered, its losses during these processes may amount to 3–5% of its weight, and, taken together with the losses during unloading and stockpiling, they constitute an appreciable item of costs in calculating the cost of energy obtained during its firing. In addition, the dust generated during its transportation and stockpiling pollutes the terrain along the transportation route and in the vicinity of the storehouse.

The technological properties of fuel coal–water suspensions (as those of any other suspensions) are determined by the following parameters:

(i) the content of solid phase (coal);

(ii) the dispersion of solid phase (the granulometric composition and specific surface of coal containing mineral impurities);

(iii) the viscosity and its dependence on transportation velocity and temperature;

(iv) the dynamic stability (when suspension is transported by pipelines or in tankers) and the static stability (when it is stored in reservoirs);

(v) the composition, properties, and necessary content of chemical additions in the form of surfactants (stabilizers and dispersants); and

(vi) the content and composition of mineral admixtures, including such environmentally harmful matters as sulfur compounds and other toxic substances.

An indispensable component of a technology for preparing coal–water suspension is milling of coal in mills of different types and having different power requirements. Coal–water suspension is usually prepared during the milling of coal; in this case, a mill is also used as a suspension mixer. However, schemes in which coal–water suspension is prepared in two stages are more economically efficient: coal is milled in accordance with coal pulverizing technology, after which it is mixed with water in a mixer. Sometimes—as, for example, at the Belovo–Novosibirsk terminal—the viscosity of suspension is minimized by milling the latter in ball and rod mills (coal having a bimodal granulometric composition). The preparation of coal–water suspension is completed in an additional mixer. The extent to which coal is milled depends on the purpose of suspensions and the conditions under which they are used. Suspensions designated to replace hydrocarbon fuel in internal combustion engines must be dispersed much finer than those used at thermal power stations instead of fuel oil. The upper limit of coal particle sizes is established for each method of suspension usage, proceeding from the requirements of minimizing the ratio of unburned carbon and expenditures for dispersing the fuel. A method for preparing suspension must ensure its minimum viscosity, highest stability, and minimum costs for fine milling. The costs for preparing coal suspensions (milling and mixing) taken together with the costs for surfactants determine to a considerable extent the cost of coal suspensions and their economic competitiveness with respect to other kinds of fuel.

All other properties of coal (heating value, ash content, mineral composition, and initial moisture content) being equal, and provided that the costs for preparing coal–water suspension are equal as well, the main quality of a suspension is determined by its rheological characteristics (viscosity and stability), which depend on many factors. Among these are the properties of a dispersion medium; the composition, density, and contents of the dispersed phase; its granulometric composition; the liophobic–liophylic balance of a phase interface surface; and the energy of surface interaction between the phases. In order to improve the technological characteristics of coal–water suspensions and to improve the quality of their atomization during firing, surfactants are as a rule added to them; these can be introduced either at the stage of milling or mixing. The molecular structure of surfactants and their content in the suspension are essential factors here.

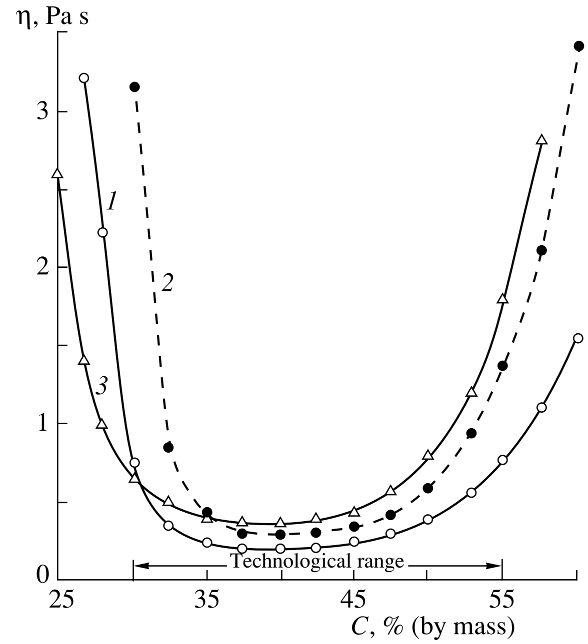

Fig. 3. Effective viscosity of coal–water suspension (having coal content $C = 63.5\%$) versus the percentage of fine fraction (smaller than 60 μm in size). (*1*) and (*2*) large fraction (125–259 μm): (*1*) Newly prepared, (*2*) the same after 7 days, and (*3*) large fraction (125–250 μm having 5% of particles measuring less than 125 μm.

Suspension is a metastable colloid system. Its stability with respect to a solid phase precipitating depends on the physicochemical properties of coal particles, known as the formation of a spatial frame in the suspension. However, even well-stabilized suspensions tend to become stratified within a matter of a few days. As a result, dense sediment appears, which can only be returned to a suspended state by intensive agitation. Homogenization is an indispensable element in the chain for preparing CWF that has to be transported. The electric energy requirements for preparing CWF at the Belovo–Novosibirsk terminal totaled 72 kW h/t, of which 14 kW h/t were spent for homogenization. The costs this facility had to pay for surfactants were three times

Table 1. Optimal parameters of coal–water suspension

Parameter	Application fields				
	Coal-fired thermal power stations	Fuel-oil-fired thermal power stations	Boiler houses	Internal-combustion engines	Gas generators
Content of coal, % (by mass)	60…70	60…70	62…65	48…54	50…65
Viscosity, Pa s, at 100 s^{-1}, not higher than	1.0	1.0	0.5	0.3	1.2
Content of sulfur in dry coal, % (by mass), not higher than	1.2	1.2	0.8	0.6	1.0
Mean heating value, kJ/kg	21000	21000	21000	14600	18800
Ash content in coal, % (by mass)	>12	3…5	2…6	0.5…1.0	>12
Particle size, μm, not more than	250	150	45	25	200
Stability, days, not less than	120	120	180	10	10

that for electricity. The overall costs were higher than the cost of coal in the region where it was produced.

The optimum (in terms of electrical energy spent for suspension preparation) parameters of CWFs intended for different application fields are given in Table 1. Enrichment of ordinary coal should be regarded as a desirable element of CWF fabrication for all kinds of CWF and in all cases of its application. Vehicle fuel for internal combustion engines is fabricated from coal that should be enriched and demineralized to have a residual ash content of not more than 2%. Some parameters constituting the overall balance of energy cost have mutually opposite influence. For example, the more dispersed is coal, the more stable are suspensions, and the easier is their firing. At the same time, the more finely coal is dispersed, the higher are the costs for milling it, the more viscous are the suspensions (given the same content of coal, as well as the composition and content of surfactants in them), and, consequently, the higher are the transportation cost and the cost for surfactants. Insofar as the economics of the production, transportation, and firing of coal-suspension fuel is concerned, the content of coal in it is one of the decisive factors, especially as regards the transportation of water suspensions and the efficiency of burning them.

One important economic component of suspension technologies is the cost of retrofitting power installations. Internal combustion engines must inevitably be retrofitted and their designs made more sophisticated because solid fuel has relatively high abrasiveness and its flammability and combustion rate are lower than those of petroleum fuel and gas. The more finely coal is dispersed and the lower the content of mineral impurities in it, the lower is the wear and, accordingly, the longer is the service life of the power units modified to operate on coal–water suspension. Fuel-oil-fired thermal power stations must be equipped with ash-removal systems if the ash content of coal is higher than 5%.

An analysis of the results from a large number of studies [5–17] allows us to consider that the optimal technical characteristics of coal–water suspensions have now become settled for different kinds of usage (see Table 1). These characteristics reflect the technological, economic, and environmental factors pertinent to the preparation and use of coal–water suspensions. It goes without saying that these characteristics correspond only to the present-day level of technologies. The technical properties of coal–water suspensions optimal in terms of the economic indicator will change with the development of these technologies, for example, as a result of more wear-resistant and heat-resistant metals and composite materials becoming a factory standard, and the replacement of petroleum products by coal suspension fuel will become a more and more profitable choice.

COAL–WATER FUEL INSTEAD OF COAL

The industrial use of CWF in heating boiler houses designed for firing coal, as well as the use of slack suspensions, was found to be inefficient both economically and technically.[2] Research and development activities in this field have been carried out in Russia. These activities have now been stopped; the installations constructed within the framework of these activities, after a short-term adjustment work, have been dismantled.

That CWF would turn to be unprofitable for coal-fired thermal power stations and heating boiler houses should be considered quite an expectable result. The costs for preparing CWF and firing it as liquid fuel are considerably higher than those associated with fuel-bed firing and firing in coal-dust flames. Under the conditions that existed, heating boiler houses had to be additionally equipped with plants for preparing, storing, and admitting suspension. This would require capital

[2] When coal has an ash content of 10–12% or more.

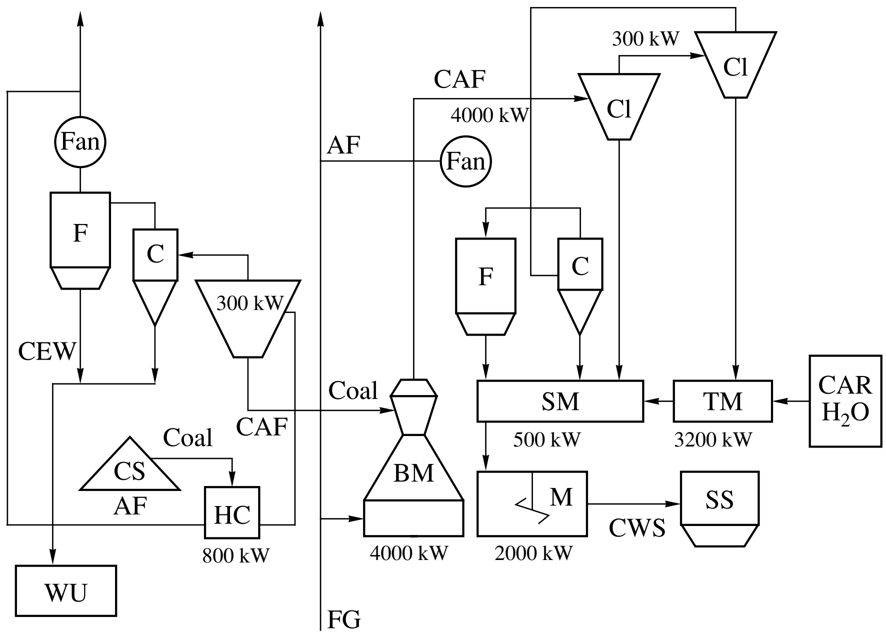

Fig. 4. Schematic diagram of the process line for preparing coal–water suspension with partial coal enrichment. The design capacity of the line is 400–500 t/h. CS—coal storage, HC—hammer crusher, Cl—classifier, C—cyclone, F—filter, BM—middle-speed mill, TM—tube mill, CAR—reservoir for chemical additives, SM—screw mixer, M—blade mixer, SS—suspension storage, CEW—coal enrichment wastes, CAF—coal–air flow, AF—air flow, FG—fuel gas, and WU—waste utilization unit.

investments and additional production areas. The fuel paths and burners had to be retrofitted as well.

When constructed in a version optimal in terms of costs, an industrial-scale plant for fabricating CWF is a milling module comprising a crusher and a mill furnished with a system for supplying and dosing coal, a dust removal system equipped with a bag filter and an exhauster, cyclones for finished powdered coal, and mixers for preparing suspension (Fig. 4). The equipment arranged downstream of the plant includes a device for taking away finished suspension (furnished with a trump iron catcher), pulp pumps with a mixer and an intermediate reservoir for finished suspension, and a second pump for feeding suspension to the burners. If we wish CWF to be burned in a flame, the combustion chamber must be equipped with burners having a wearing capacity much higher than that of burners for firing dry coal.

The electric energy consumed by modern hammer and middle-speed mills for milling dry coal to a coarseness characterized by a residue on a sieve with 250-μm cells of not more than 5% is 12–15 kW h/t. The costs due to the wear of the metal of milling members do not exceed those for electric energy. That the atmosphere in the mill volume is reducing in nature almost completely prevents chemical corrosion from occurring.

The electrical energy consumed for preparing CWF using the most primitive (and therefore most widely applied) scheme, according to which coal is milled while part of suspension, is considerably larger than that for preparing dry coal dust having the same dispersion. This energy is not less than 25 kW h/t. Such a large consumption is because suspension, a substance that offers high resistance to the motion of milling members, and coal particles in which are not readily fragmented, has high viscosity. The mechanical, as well as corrosion, wear of milling members is from three to five times (depending on the steel grade) higher than when dry coal is milled.

The above expenditures of electrical energy and metal relate to a technology that does not imply a need to transport CWF by pipeline. If the CWF we are dealing with has to be transported, its viscosity and concentration must be optimized to suit the purpose. To do so, approximately one-third of the coal must be milled so that its particles become less than 60 μm in size, an operation that will cause the expenditures for preparing it to increase by a factor of 3. The fuel mass is stabilized using surfactants, the cost of which in terms of specific consumption is commensurable with that of coal.

When suspensions are prepared using a direct method, the electric energy consumed by the mill (25 kW h/t) is transformed into heat and is mainly spent for evaporating the water contained in the CWF. Calculations and experimental data have shown that approximately 15 kg of water per ton of CWF is evaporated during its preparation. Given a mill capacity of, say, 3 t/h, 45 kg of water will be evaporated for 1 h of its operation, or 1 t for 24 h. The milling plant must therefore be equipped with a steam removal system to prevent steam from condensing in the premises. In contrast, the mechanical energy of milling, which is supplied to the working volume of dry coal dust preparation machines together with the heat of furnace gases, is usefully employed there for additionally drying the coal. The steam generated during the process is removed by the milling plant's aspiration system.

The expenditures for preparing CWF in accordance with the primitive scheme (without taking into account the cost of water in it) are several times higher than those for preparing coal dust having the same dispersion (coal particles in dry mills are separated by size using the pneumatic separation method, which allows energy requirements to be almost halved; in addition, the wear rate of dry mills is several times lower). These expenditures are not less than 12% of the cost of coal and account for a considerable fraction of the cost of electricity generated. If the CWF has to be transported by pipelines, the expenditures for preparing it become significantly higher. The combustion process is inevitably preceded by water being completely evaporated. Thermal calculations have shown that around 5% of the coal contained in CWF is spent during its firing for evaporation of water (1% for every 10% of water). The experimental data obtained at the All-Russia Thermal Engineering Institute have shown that the combustion temperature is approximately 150°C lower, the fraction of unburned carbon and incomplete combustion ratio are by at least 2–3% higher, and the boiler efficiency is 2–5% lower when firing CWF than they are when coal dust is fired.[3]

The above factors cause the technology of CWF to be considerably inferior to the coal-dust technology in terms of capital outlays and operational costs.

The environmental advantages of CWF, which are commonly referred to, are questionable and lack sufficient substantiation. The emissions of pollutants into the atmosphere (except nitrogen oxides), like the composition of ash and slag, are determined by the chemical composition of mineral inclusions in coal and by the completeness of its burnout. They cannot be reduced by adding water to coal.

Given such a coarse milling as that used to obtain CWF, mechanochemical effects do not show themselves [18–20]. For these reasons, attempts to ascribe to CWF certain special properties not characteristic of coal (a higher heating value, a more complete combustion, a lower ignition temperature, and lower emissions of sulfur and carbon) should be considered a technical hoax.

Experiments have shown that the emissions of nitrogen oxides can be reduced by approximately a factor of 2. This is a consequence of the flame temperature dropping due to the expenditure of heat for evaporating water. The same result can be obtained by merely adding water to the flame in which dry coal is burned. However, decreasing the flame temperature makes the combustion less stable and inevitably results in a lower efficiency of thermal units.

[3] Report on Pilot Commercial Tests of Coal-Water Fuel at the Novosibirsk TETs-5 Cogeneration Station.

SUSPENSION FUEL FOR FUEL-OIL-FIRED THERMAL POWER STATIONS AND BOILER HOUSES

There are two circumstances that make the issue of using CWF relevant for fuel-oil-fired thermal power stations. The first is dictated by the strategic interests of countries with power industries based on petroleum fuels (e.g., Japan), and the second is dictated by economic challenges. Now that petroleum is refined in an increasingly deep manner and that a larger amount of light fractions is yielded, the prices for fuel oil tend to increase even under the conditions in which prices for petroleum remain relatively stable. The prices for fuel oil are now higher than those for crude oil.

The use in fuel-oil-fired thermal power stations and boiler houses of suspensions made of coal having a typical ash content (10–12% or higher) will generate a need to equip these power facilities with ash- and slag-removal systems similar to those used at coal-fired thermal power stations. However, if the ash content of suspensions does not exceed 5%, the dust collection systems used at fuel-oil-fired thermal power stations will need only moderate retrofitting. It is well known that one does not need to resort to expensive methods of chemical demineralization or oil-assisted agglomeration for enriching coal to such an ash content. Coal can well be enriched to an ash content of 5% using the technology for sedimentation in cyclones containing heavy media and by flotation in columns.

The use of coal–water suspensions as a substitute for part of fuel oil is practiced on a commercial scale at thermal power stations and heating boiler houses. The advances achieved in Japan are especially indicative in this respect (Fig. 5). Mitsubishi Corp. has become the first firm to develop an industrial technology for fabricating and utilizing coal–fuel oil suspensions. Such a fuel has been used in two power units each having a capacity of 265 MW since 1985. A 7.5-MW pilot thermal power station firing coal–water suspension is in operation that consumes fuel at a rate of 3.2 t/h. Power-generating units having capacities of 60 and 100 MW consume coal–water suspension at a rate of up to 21 t/h. Some coastal thermal power stations have been equipped with retrofitted combustion and ash removal systems; this allows them to use coal–water fuel on an industrial scale. Suspension is burned together with fuel oil, usually at night or when the load in the power system drops considerably.

Pilot-commercial plants for producing coal–water suspension that are intended for replacing fuel oil have been constructed and are now in operation in the United States, Italy, Sweden, Germany, and China.

SUSPENSION COAL FUEL FOR INTERNAL COMBUSTION ENGINES

The heat-generating equipment used at thermal power stations and boiler houses employs a two-circuit scheme. The thermal energy of fuel combustion products is transferred to the working medium (steam) through heat-transfer walls, which separate fuel chambers from the evaporation circuit. On the contrary, the combustion products, and with them steam, that are generated in internal combustion engines serve as the overall working medium in the combustion chamber's volume commonly shared by these products and steam. Part of the heat that is released during fuel combustion is spent for evaporating water, thus making it easier to cool the engine. Therefore, the use of coal–water suspensions in internal combustion engines is economically more promising in terms of the overall thermal effect than it is in two-circuit thermal units.

It is of utmost importance for internal combustion engines to achieve good atomization of fuel and minimal wear of working surfaces. It is precisely these two problems on which efforts for developing the technical and technological aspects of creating a coal-based vehicle fuel and sophisticating the design of engines are focused.

That the use in diesels and gas turbines of CWF is a burning problem from the economic point of view is determined by the following. These machines are mainly used as drives for vehicles, which are known to consume approximately one-half of the energy resources produced on the Earth, including virtually the entire volume of light petroleum-refinery products and part of natural gas. It is worthy of note that vehicles also account for the most of the toxic emissions polluting the atmosphere. Both problems need to be solved, i.e., the consumption of petroleum products has to be decreased and the emissions of toxic combustion products (sulfur and nitrogen oxides, as well as benz(a)pyrenes and asphaltenes) have to be reduced. If we wish the use of CWF for internal combustion engines to become reality, economically efficient technologies for deep demineralization of coal and its superfine milling must be developed, conditions must be provided for coal suspensions be combusted in full-valued manner, and the wear of engine parts must be minimized. Technological solutions must be found for neutralizing or entrapping the emissions generated during the combustion of coal fuel.

Attempts to use coal fuel in diesel engines have a long-standing history. The first experiments with pulverized coal were carried out by O. Diesel in 1982. Research activities in this field were continued in Germany till 1945. Technical difficulties encountered by researchers in trying to obtain deeply demineralized coal, complete combustion, and acceptable engine wear forced them to stop these activities. Investigations into the problem of using coal fuel for engines were resumed in the United States in 1975. Research activities carried out in recent years [21–24] have resulted in

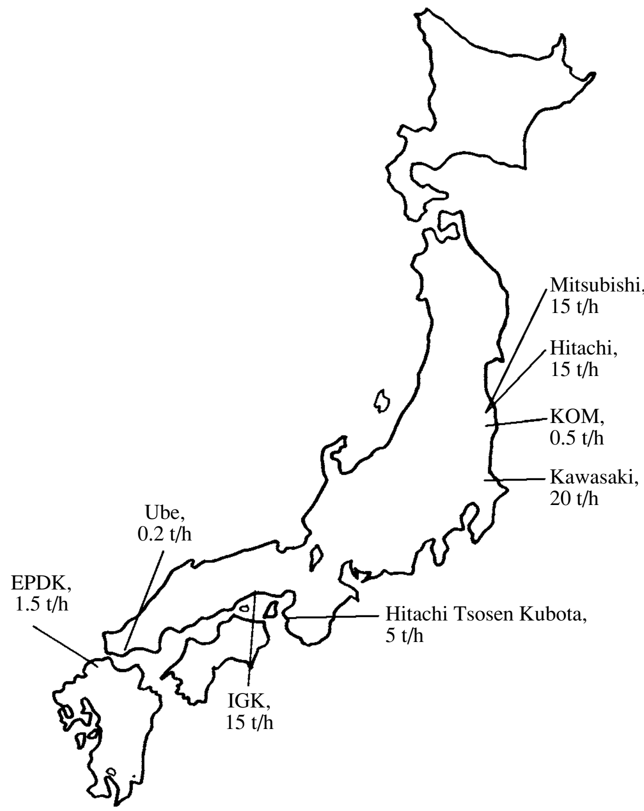

Fig. 5. Locations and capacities of plants for fabrication and utilization of coal–water suspensions (jointly with coal) in Japan.

achievements made both in the technology for preparing fuel suspensions with properties in line with those required for engines and in tailoring the designs of engines for combusting coal fuel in them instead of petroleum fuel. CWF-fired engines and technologies for preparing CWFs have now been developed that make their commercial use profitable under conditions in which petroleum is sold at very high prices.

Suspension fuel for vehicles can be prepared from black and brown coals having high content of volatiles. Vehicle CWFs made on the basis of water, methanol, and diesel fuel have been studied. All other factors being equal, coal–water suspensions were found to be less viscous, which allows their good atomization in a combustion chamber to be achieved. It is difficult to make CWF self-ignite. There is no choice but to use spark plugs, diesel fuel for supporting the flame, and other methods.

The most encouraging results have been obtained with regard to the use of CWF in an adiabatic engine, a device in which the supply of hot air to the combustion chamber compensates for the consumption of heat for water evaporation and the high temperature results in a higher rate of coal combustion. The thermal efficiency of this engine is the same as during operation on a basic diesel fuel. But despite being favorable for the combus-

Table 2. Costs for energy generated by a diesel operating on coal fuel (averaged data)

Cost item	Costs	
	Cent/(kW h)	%
Capital investments	1.21	18.5
Operation and maintenance	0.52	8.0
Coal with transportation	1.31	20.0
Fabrication of coal–water suspension	2.20	33.7
Purification of emissions	1.03	15.7
Fuel transportation	0.27	4.1
Total	6.54	100
Including:		
fuel	3.78	57.8
engine	2.76	42.2

tion of coal particles, the high temperature inherent in an adiabatic engine results in incomplete combustion of the liquid components of a suspension obtained on the basis of methanol or diesel fuel.

The content of nitrogen oxides in the products from combusting CWF was found to be approximately a factor of two lower than in the products from combusting diesel fuel. The content of sulfur oxides depends entirely on their concentration in the initial coal, i.e., on the extent to which it is purified of mineral admixtures; the coal purification ratio must be very high. The content of dust in the products from combusting CWF is several times higher than it is in products from combusting diesel fuel. The exhaust gases generated during the combustion of coal need to be specially purified.

The most complicated and expensive operations used in the technology for preparing CWF (as well as pulverized coal) are fine milling to micron-size particles and deep demineralization of such a dispersed mass. Coal–water suspension, which is the most practical coal suspension, is milled using different types of mills. It has been shown both experimentally and theoretically that power-intensive mills (vibration mills, attritors, and others) are more economically efficient for fine milling of fuel—in particular, coal—than are widely used ball drum and tube mills [18, 24, 25].

Coal intended for preparing vehicle fuel is demineralized in two stages. At the first stage, coal undergoes physicochemical enrichment using highly efficient methods, such as flotation in columns or separation in heavy media. The shortcomings of these methods are that they give a low yield of target product and large amounts of waste coal. The second stage consists of subjecting coal to chemical demineralization to obtain an ash content of less than 2%. Although featuring low loss of coal, this stage accounts for the major part of the cost for the fabrication of coal fuel for engines.

The advances achieved in the use of coal suspensions for internal combustion engines are quite impressive. In the United States, General Electric Corp. has implemented a project for changing a 12-cylinder medium-speed diesel engine of a 1.8-MW railway locomotive over to operation on CWF. Long-term (for more than 600 h) ride tests of this engine have been carried out, and its performance characteristics have been obtained. The CWF for the engine was prepared using bituminous coal milled to particles 5–6 μm in size. The coal demineralization ratio (in terms of residual ash content) was varied from 0.7 to 2.8%. The CWF injection system ensured a coal combustion completeness of not lower than 98%. The measured thermal efficiency of the diesel was found to be 0.85 of that when the engine operates on diesel fuel. A system for purifying and decontaminating exhaust gases has been developed, whose efficiency is equal to 99.5% for entrapping solid particles and 90% for sulfur and nitrogen oxides.

The Sulzer and Kuper-Bessemer firms have carried out long-term tests of CWF in stationary diesel engines having capacities of 1.4 and 1.8 MW. These tests have shown that the use of CWF in diesel engines holds promise (at prices for diesel fuel and coal corresponding to their 1997 level).

The cost of energy (in the United States) obtained when CWF is used in a locomotive runs to $3.3/GJ, which is considerably higher than the cost of energy obtained from combusting dry coal ($1.25–1.8/GJ), but lower than the cost of energy obtained when diesel fuel is used. At present, the costs for generating energy in a diesel engine firing coal–water fuel are approximately the same as those when fuel oil is used. The costs, which were calculated in 1998 prices, take into account all expenses, including those for purifying the emissions (Table 2).

The firm Allison Gas Turbine (a division of General Motors) has successfully carried out tests of CWF in a 4.0-MW industrial-grade gas turbine. The power installation uses a two-stage combustion scheme. The first stage comprises a CWF gasification system equipped with devices for removing dust and harmful impurities from the producer gas. The CWF used in the power installation had a coal content of 50%; the ash content of this coal was varied from 0.8 to 5.6%. The design purification ratio of the producer gas is 99.9%, and the working cycle to the regeneration of filters has a duration of 370 h. The fuel is combusted in the gasification path with a completeness of not less than 96%. Such a system ensures long-terms operation of the turbine and environmental safety. Similar activities, and with similar results, have been accomplished by the Amax and Ottiska firms.

The calculated cost of energy obtained from combusting coal fuel in gas turbines is equal to $3.0–3.2/GJ, a value almost equal to the cost of energy obtained when coal fuel is combusted in a diesel engine. The economic efficiency of coal fuel can be increased by improving the methods for fine milling and demineralization of coal, as well as by improving the design of engines.

According to different estimates, the specific costs for demineralization amount to \$1.57–2.85/GJ; the overall specific costs for the generation of energy in diesels and turbines with the use of coal fuel total 6.40–6.85 c/(kW h). The specific cost of energy obtained by combusting petroleum fuel in engines, calculated in prices corresponding to the same time, is 3–5 c/(kW h). These figures were calculated taking into account profit (10%) and depreciation deductions (12%).

The reserves for reducing the costs for generation of energy in internal combustion engines using suspensions lie in improving the technology for fine milling and deep demineralization of coal, taken in combination with making commercial use of products from leaching minerals, and in modifying the design of engines. According to the data available, the use of up-to-date technologies in this field makes suspension fuel competitive with petroleum fuel (Table 3). Preliminary calculations have shown that the mechanochemical technology for demineralization to an ash content of less than 2% that was developed by the authors is more profitable than the others (in comparable arbitrary energy units). In addition, this technology is virtually wasteless and environmentally safe.

Table 3. Relative costs, kg/t of product, for preparing CWF from coal demineralized to a residual ash content of 2%

Kind of costs	Column flotation	Oil agglomeration	Leaching	
			Pressure	Mechanochemical
Milling	159	159	159	159
Wear of mills	250	250	250	250
Demineralization	500	500	1000	714
Capital	1000	1500	2000	1000
Total	3273	3318	3483	2172
Relative	1	1.01	1.06	0.66

COAL–WATER SUSPENSIONS FOR GAS GENERATORS AND COMBINED-CYCLE PLANTS

Two ways of using highly purified and finely dispersed suspensions in generators of energy have been determined. The first implies that fuel is burned directly in the form of suspensions (which was discussed above). The second implies that suspension is preliminarily gasified, followed by the combustion of producer gas in gas turbines; the excess thermal energy of the gas generator is utilized in the form of superheated steam in a steam turbine. This line of development has found use in combined-cycle plants. The potential profitability of using CWF in gas generators stems from the fact that suspension can be supplied to a reactor using high-pressure pumps, thus allowing gas generators to be charged in a continuous manner. In this case, the sluice chambers, shutters, and feeders that are used for supporting the operation of gas generators in the periodic mode at high pressure and temperature—equipment that is very complex to operate on dry fuel—are no longer needed. Part of the water contained in CWF (approximately half of it) is usefully spent in gas generators for generating hydrogen and carbon oxide as a result of dissociation that proceeds at high temperature and pressure. Water (in an amount of 15% of the coal mass) is also fed to usual gas generators that operate on coal having a moisture content of 10–15%. With the water contained in CWF used in this way, one does not need to spend energy for its evaporation when suspensions are burned directly.

Subjecting coal and other energy carriers to preliminary gasification followed by using the producer gas in gas turbines (and diesel engines) and superheated steam in steam turbines is currently considered the most advanced and promising technology in power engineering. The rubbing parts used in gas generator installations are considerably fewer in number than those found in engines (note that it is these parts the wear of which has a considerable effect on the ability of a machine to operate). The use of high temperature and pressure allows fuel to be converted into combustible gas with a high degree of completeness. The cost of purifying this gas from dust and from sulfur and nitrogen oxides is much lower than that of purifying the combustion products, because the mass of the producer gas is 9–12 times smaller than that of combustion products and, accordingly, the concentration of harmful impurities that have to be removed is higher by the same factor. In addition, the pressure at which the producer gas is purified is 1.0–1.5 MPa. Consequently, the volume of this gas is approximately 100 times smaller than the volume the fuel combustion products subject to purification occupy at atmospheric pressure.

If combustible gas is fired as fuel, there is almost no need to modify existing equipment, nor is there any additional wear of the working parts of power installations under the effect of solid fuel. The superheated steam produced in combined-cycle plants equipped with gas generators is used in steam turbines, the capacity of which is approximately half that of the plant's gas turbine. As a result, such installations allow the energy of the coal being combusted to be used in the fullest and most rational manner. The requirements imposed on the dispersion composition of fuel, the degree of its enrichment, and on the viscosity and stability of suspensions are very moderate (see Table 1).

Combined-cycle plants for capacities ranging from 60 to 300 MW have been constructed in the United States, the Netherlands, Germany, and Spain. There are two thermal power stations in the United States (one in

Indiana and the other in Florida) designed for firing coal–water suspension. The thermal power station in Indiana is equipped with a 191-MW gas turbine and a 110-MW steam turbine; the power station in Florida is equipped with a 192-MW gas turbine and a 130-MW steam turbine. The calculated (and measured) efficiencies of these stations are equal to 42%, whereas those of usual thermal power stations are equal to 35%.

TECHNICAL AND ECONOMIC PROSPECTS FOR USING SUSPENSION COAL FUEL

The low prices for petroleum that existed late in the past century resulted in that the majority of projects for suspension fuel were postponed for indefinite time. With the prices for petroleum that existed in 1999 (around $8–9 instead of the previous $18–25 per barrel), the use of coal–water suspensions instead of fuel oil was obviously unprofitable, even provided that coal was purchased at the lowest price (of those existing at that time).

Suspension coal fuel employing petroleum products, alcohols, or (as a rule) water as dispersion medium was considered a promising alternative for power engineering provided that the price for petroleum exceeds $25–30 per barrel (as at present). It was believed that the upper limit of petroleum prices would depend in much on coal technologies. Hopes were also placed on these technologies as a means for solving the environmental problems associated with power supply, which became especially pressing in view of accidents at nuclear power stations and pollution of the natural environment with petroleum.

The first programs on developing technologies for preparing and using CWF, as well as many of those to follow, have been implemented. The results from a wide volume of investigations and technological developments that had been carried out in this field were presented at annual international conferences on coal technologies, which were convoked and held in Florida under the aegis and financial support of the US Department of Energy (the conference held in 2005 was the 29th one). The published proceedings of these conferences (up to the year 2000) contain valuable information on the subject. We also know of other serious papers on coal–water fuels published in American, Russian, Chinese, Japanese, and other sources that reported the results of investigations, as well as from design and technological developments.

The period when the interest in water–fuel technologies was at its peak saw governments and large companies of some industrially developed countries earmarking considerable money for extensive programs, the scope of which included investigations and economic and environmental analyses of suspension fuel. Researchers and process engineers working at research centers owned by public and private companies were charged with the task of developing industrial-grade technologies for obtaining CWF that would be at least as good as petroleum products in economic and environmental indicators. Industrially developed countries saw their objective in making their national economy less dependent in the future on the political climate in oil-producing regions (the states of the Persian Gulf and others). It was a priori believed that suspension fuel could be used in accordance with the technology for combusting liquid fuel without spending much money for retrofitting existing equipment. In the 1980s and subsequent years, technologies for preparing and combusting coal suspensions were developed. Investigations and pilot-commercial tests of processes for preparing coal suspensions and transporting them by pipelines (as liquid fuel) were also carried out in Russia; these activities were accomplished in a large volume and with good completeness.

After 2000, papers published on CWF became fewer and fewer in number and have now ceased almost completely. This is because, first, the technical problems related to the development and utilization of CWF were resolved and, second, this kind of fuel, despite the initial expectations, turned out to be economically inefficient even at very high prices for petroleum. Industrially developed countries have chosen the path of developing technologies for using renewable energy carriers. Despite possible expectations, today's very high prices for petroleum and gas have not given rise to renewed interest in coal suspensions. However, this does not mean that developments in the field of coal suspensions will be of no need in the future.

It should be pointed out in conclusion that the information presented in this paper is based on an analysis and comparison of numerous publications. Since the full list of these publications is too long to be given here, the list of references laid out below contains only those most relevant to the problem considered. These papers describe technologies for obtaining highly filled low-viscous suspensions prepared from Russian coals and for demineralizing coals to an ash content of less than 1% with minimum losses. Experience with transporting suspensions over long distances has been generalized, factors that caused this technology to have not met with success have been revealed, ways of removing these obstacles have been suggested; and the most economically efficient industrial projects for preparing CWF have been worked out [5, 6, 8, 9, 11–13, 24–30].

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