Environmentally friendly thermal power plant based on the principle of a multi-product complex at vortex burning of the Berezovsky coal of the Kansko-Achinsk basin

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Abstract According to the Energy Program of Russia until 2030, the formation of coal power is associated with large thermal power plants on low-grade coals and supercritical steam parameters. An increase in the proportion of low-quality coal leads to a sharp increase in toxic emissions in flue gases, liquid effluents and ash and slag waste. The article considers the scientific and technical bases and circuit solutions for the creation of environmentally friendly thermal power plants (EFTPP) on the Berezovsky coal of the Kansko-Achinsk Basin (KAB) with vortex combustion technology based on the principle of a multi-complex with the production of not only the main products (electric and thermal energy), but additional waste with consumer properties. Multi-product complex (MPC) is a series of road construction plants and agricultural enterprises, associated with the TPP and efficiently using wastes for construction, metallurgy and various agricultural products. The performed calculations and analysis of technical and economic indicators have shown that with the existing equipment, prices and tariffs for the products, the EFTPP will pay off more than two times during the life cycle. After 8 years from the beginning of construction the MPC starts generating profit.

1. Introduction
The main direction of the development of modern coal energy is application of advanced technologies for the use of coal at environmentally friendly thermal power plants [1, 2]. According to the Energy Strategy of Russia's development up to 2030 [3] the accelerated development of electric and thermal generation is associated primarily with the large thermal power plants on low-grade coal and supercritical steam parameters. The increase in the share of low-quality coal in the energy sector leads to an increase in emissions of toxic ingredients in flue gases, aggressive liquid effluents, ash and slag waste, etc. Cleaning only the flue gases of TPP from pollutants to fit sanitary norms at foreign coal-fired power plants requires equipment worth up to 30% of the total cost of thermal power plants, while the specific fuel consumption increases by 5%, and the cost of electricity – by 25%.

2. Requirements for environmentally friendly TPP (EFTPP)
These requirements were first formulated by V. I. Dobrokhotov [4]. The distinctive features of EFTPP with a capacity of 6.4 GW (8 power units of 800 MW each) developed by us are as follows:

- steam generator of vortex type;
- disposal of ash and slag waste;
- electron beam neutralization directly in flue gases;
- complete cleaning of aggressive liquid effluents (thermal desalination);
- heat recovery of low-potential sources (heat pumps);
- plasma ignition and illumination of a pulverized coal torch;
- closed fuel storages with the system of dust suppression and water wash.

3. Vortex-type steam generator for power unit of 800 MW using Berezovsky coal of KAB

Characteristic features of Berezovsky coal of KAB (BC KAB) are: low ash content, low content of sulfur and nitrogen in the fuel, and high content of CaO. With increasing ash the content of CaO decreases and that of SiO₂ and AlO₂ increases, which conditions their high slagging capacity. When burning BC KAB, strong primary deposits based on calcium sulfide are formed on convective and radiation-convective surfaces, and the temperature of the slagging beginning is 950 °C, which is the minimum for all fuels in Russia. As the experience of KAB combustion shows, the behavior of mineral components of ash in the furnace depends on the organization of the combustion process, in particular, on the internal aerodynamics. Therefore, a steam generator with a combustion device, based on a high-temperature forced vortex with a horizontal axis by N.V. Golovanov (CKTI Ltd.) is used in the developed EFTPP, in the reconstructed version with a steam capacity of 2650 t/h and with supercritical steam parameters of 25.5 MPa, 560/545 °C for the power unit of 800 MW. The design advantages are: rational weight and size characteristics, single-frontal arrangement of burners, and high maneuvering properties.

As it is noted in works [5, 6] at high-temperature burning of BC KAB in a vortex furnace there is full melting and averaging of all mass of ash with high efficiency of slag trapping. High-temperature treatment of ash in a swirling flow furthers the particle contact, while significantly reducing the content of free CaO in fly ash due to Ca binding with Si and Al oxides. The latter leads to the formation of stable aluminosilicate compounds, which causes the sulfatization of calcium. In this primary combustion, the layer of slag on the heating surfaces is less sulphited and, therefore, less durable [7]. In addition, due to the separation of Si and Al oxides from the slag, the latter becomes more fusible, and the content of Ca increases in the entrainment, which leads to an increase in the temperature of slagging beginning by 50-70 °C. This allows significantly increasing the temperature of the gases at the furnace outlet.

The dimensions of the steam generator with a vortex furnace are reduced by the use of two-light vertical screens and screens in the cooling chamber. To reduce the concentration of nitrogen oxides in the created vortex-type steam generator (PVT-800), two-stage combustion of fuel is provided by supplying part of the drying agent in the air channel of the burner and introducing additional air above the main burners. High-concentration dust (PVC) must be supplied under pressure.

As a starting point for the technical, economic and environmental comparison of the power unit with the PVT-800 steam generator, the 800 MW power unit of Berezovskaya (GRES) HPS-1 with the P-67 steam generator with dry slag removal was adopted.

4. Technological scheme of power unit with capacity of 800 MW of EFTPP based on the principle of multi-product complex (MPC)

The main approach to the creation of a coal-fired power EFTPP is to form associated enterprises, factories, plants, agricultural enterprises, etc. around the power plant. They should be intended for the processing of almost all types of waste, followed by the production of a wide range of products with
consumer properties. Figure 1 shows the scheme of waste disposal of thermal power plants. EFTPP with innovative technologies of waste processing, in our opinion, should form effective resource-saving closed-cycle energy of Russia in the future.

Let us focus on the features of EBP for flue gas neutralization. This innovative method belongs to the oxidative type of combined purification of gases from SO₂ and NOₓ. Depending on the modification of the method, toxic products can be extracted in the form of either a mixture of nitrate and ammonium sulfate (mineral fertilizers), or in the form of dilute acids, which is important. The most well-known is the Japanese technological solution of EBP called "EBARA-process" [9].

According to broad estimates [10], the cost of installing an EBP of the power unit of 800 MW is approximately 96 million US dollars, and the cost of separate cleaning by traditional methods (catalytic and lime) is more than 160 million US dollars. This will require approximately 11-14 MW of total power for the accelerators. At radiation doses of 15-20 J/g, the efficiency for SO₂ neutralization reaches 95%, and for NOₓ it is 80%. When burning 1 kg of BC KAB at an excess air of 1.15, 5.76 m³ of gas combustion products is formed. At that, the hourly output of one power unit will be 2730 thousand m³, and that of the entire plant will be 21.84 million m³. The gross gas emission of combustion products into the atmosphere with 7040 hours of use of the installed capacity will be 153.7 billion m³ per year. In the considered EFTPP with cleaning efficiency of up to ecologically required level for NOₓ from 0.5 g/mm³ to 0.15 g/nm³ (our computer calculations on Mitchell–Tarbell model [11]), and for SO₂ from 0.59 to 0.2 g/nm³ it is required to neutralize 53.81 million tons of NOₓ and 59.96 million tons of SO₂ a year.

Implementation of the proposed EBP of flue gas requires investments of 420 million dollars [12]. At that, capital investments into the EBP unit for EFTPP with a capacity of 6.4 GW are about 2.7 billion US dollars. The analysis of traditional methods of denitrification and desulfurization (selective catalytic reduction, absorption, etc.) shows that, in this case, the capital costs are almost doubled. In light of the current environmental and economic requirements for thermal power plants, the introduction of EBP is promising. If ammonia is used in EBP schemes in an equimolar amount, the yield of a mixture of sulfate and nitrate of ammonium (mineral fertilizers) will be approximately 3.1
kg/s [13] per 800 MW power unit, which corresponds to an annual yield of 507 thousand tons). Revenue from the sale of this amount of fertilizers at current prices will be 164.8 million US dollars/year.

5. Ash and slag waste and solid volatile emissions of TPP
The output of ash and slag from EFTPP with a capacity of 6.4 GW when burning BC KAB (when $A \sim 6\%$) in terms of material balance will be $\sim 1230$ thousand tons/year. In VSG of 800 MW at liquid slag removal through the bottom tap hole of the furnace $\sim 65\%$ of slag is removed. The coefficient of fly ash entrainment is $\alpha_{\text{entr}} = 0.35$. At the use of the "EBARA-process" of joint cleaning of flue gas components, an additional stage (second) of ash entrainment in the form of a hose filter is installed. As a result, the annual amount of fly ash detained in electric filters and hose filters throughout the entire EFTPP will be 630 thousand tons/year. Mass fraction of slag, which is discharged through a slag removal system is $\sim 600$ thousand tons/year. Due to high content of CaO, the system of hydraulic slag removal becomes inoperable as a result of grids clogging and ash discharge with hydrate neoformations; therefore, in EFTPP, slags are supposed to be treated in dry form.

The complex effect of ash and slag waste utilization from the EFTPP will consist of the following components (figure 2):

- obtaining of a new ash binder and products based on it by the construction industry;
- elimination of ash dumps;
- improvement of the ecological state of the ambient nature;
- the real prospect of creating technologies for the production of waste-based building materials, saving energy, raw materials and water resources.
- 200 million tons of cement per year (for comparison, in Siberia the existing annual level of production is about 15 million tons);
- 17 billion pieces of silicate brick (in Siberia $\sim 20$ million pieces per year);
- 0.43 million tons of ferrosilicon;
- calcium carbide in the amount of 1.2 million tons and 4.2 million tons of calcium cyanamide (the current level of production of these substances per year is 0.24 million tons and 0.75 million tons, respectively).

The use of dry ash and slag from EFTPP at KAB is diverse and wide-ranging [14, 15]. The amount of ash and slag from EFTPP will be sufficient for the production.
Figure 2. Technological scheme of ash and slag utilization.

6. Neutralization of industrial effluents from EFTPP

Oil containing effluents (with a concentration of more than 30 mg/l) are cleaned first in the deoiling plant. The effluents, whose oil concentration is reduced to 0.5–1.0 mg/l, are mixed with conditionally pure waters, and in an amount of 1650 t/h enter the contact heat exchanger with a drop trap, which is simultaneously a stage of wet cleaning. Centrifugal scrubbers of All-Russian technical Institute (VTI) with a diameter of 7 m with two irrigation belts are used as contact heat exchangers. Flue gas flow through the scrubber is $792 \times 10^3$ m$^3$/h, and the number of scrubbers is 4. The temperature of the discharged water is 58 °C. This water enters the multistage evaporator of instant boiling of the design of "SPA Tekhenergoimprom" JSC, where it evaporates and cools under vacuum.

The resulting steam is condensed on the condenser tubes, and the distillate in an amount of 80 m$^3$/h is sent to the feed water circuit of the power unit. Such a system leads to the abandonment of chemical water treatment plants (CWTP) at the EFTPP, which, of course, is associated with additional cost savings. Highly mineralized brine (100-150 g/l) with a temperature of 35-40 °C from the thermal desalination plant is sent to the heat pump. Then it is cooled after the evaporator of the heat pump and discharged into the unit of granulated ash waste, which uses water with an increased concentration of mineral salts. The change over to thermal desalination of aggressive effluents using their low-potential heat, in addition to the environmental effect, has economic efficiency. The cost of the resulting feed water during thermal desalination is about 5 times lower than in CWTP plants.

7. The use of low-potential heat of 800 MW power unit

The thermal power of the low-potential heat of the power unit of 800 MW is about 4 GJ/h. The discharge water temperature is mainly small, on average about 25 °C. A small part of the heat losses have a relatively high potential; flue gases contain about ~5% and effluents with a temperature of ~35 °C contain ~6% (boiler purge water, water from the cooling system of the thermal desalination plant.) The effective utilization of this heat for heat supply and heating in convector or air heating (supply ventilation, direct calorific heating, thermal curtains) can occur with a significant economic effect. Here, the need for low potential heat in:
• the system of heat supply and hot water supply of the main building of EFTPP and auxiliary buildings of different services is 40 GJ/h,
• the system of brine supply for the instant boiling unit for the device of slag granulation is 30 GJ/h.

Conclusion
The formulated scientific-technical and technological bases of EFTPP creation on the principle of MPC, the performed calculations and the analysis of technical and economic indicators for production of various types of products with consumer properties, including from waste, have shown their technical efficiency and financial solvency. With the existing equipment, prices and tariffs for manufactured products, EFTPP for the life cycle will pay off more than two times. After eight years from the beginning of MPC construction it starts generating profit.

References
[1] Roslyakov P V, Izyumov MA Environmentally friendly technologies for the use of coal at thermal power plants (textbook). 2003 M.: MEI Publishing.
[2] Salomatov V V Environmental technologies at TPP and NPP 2006 Novosibirsk: NSTU Publishing.
[3] The energy strategy of Russia for the period up to 2030 approved by the order of the Government of the Russian Federation of November 13, 2009, No. 1715.
[4] Dobrokhotov V I 1992 Program "Clean energy" Thermal Engineering 8.
[5] Golovanov N V, Mitor V V, Itskovsky M A et al. 1979 Development and research of central steam generators with vortex furnace Proceedings of CKTI 154.
[6] Popov A A, Golovanov N V, et al. 1991 The results of development and research, pf experimental-industrial boiler unit with the boiler TPE-427. Sib. Fiz.-Tech. J. 5.
[7] Alekhnovich A I 2006 Slagging in energy boilers. Chelyabinsk: BSF PEIPK
[8] Salomatov V V, Krasinski DV, Keino AV et al. 2009 The results of physical and mathematical modeling of transport processes and combustion of solid fuel in the vortex furnace. Proceedings of the International Symposium on Combustion, Almaty
[9] Kawamura K, Shui V 1981 Radiation treatment for reforming SO$_2$ and NO$_X$ from exhaust gasas Ind. Appl. Radiat. Technol. Proc. Int. Conf. Grenoble
[10] Frank N, Kawamura R, Miller G 1987 Design notes on testing conducted during the period 1985-1986 Electron beam processing of combustion flue gases. IAEA. Vienna
[11] Salomatov V V 2012 Results of studies of combustion processes in boilers with vortex technology of combustion Thermal Engineering 6.
[12] Polyansky V A, Polyansky A M, Mikhailov S Ya et al. 2001 Evaluation of the economic efficiency of a new method of cleaning flue gases from sulfur oxides and nitrogen Economy, ecology and society of Russia in the 21st century. International scientific and practical conference St. Petersburg
[13] Belogorlivtsev V M, Koroteev A S, Rizakhanov R N et al. 1991 Study of electron beam technology in flue gas treatment systems of coal-fired power plants Izv. AN SSSR. Energy and transport 3.
[14] Volginskii A V, Ivanov I A, Vinogradov B N. 1984 The use of ash and fuel ash in the manufacture of building materials. M.: Stroiizdat
[15] Savinkina V F, Logvinenko A T 1979 Ash of Kansk-Achinsk brown coals. Novosibirsk: Nauka.