On issue of increasing profitability of automated energy technology complexes for preparation and combustion of water-coal suspensions

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Abstract. The article considers the issues of energy technological complexes economy increase on the existing techniques of water-coal suspensions preparation and burning basis due to application of highly effective control systems of electric drives and neurocontrol. The automated control system structure for the main boiler components is given. The electric drive structure is disclosed by the example of pumps (for transfer of coal-water mash and / or suspension). A system for controlling and diagnosing a heat and power complex based on a multi-zone regulator is proposed. The possibility of using neural networks for implementing the control algorithms outlined in the article is considered.

1. Introduction
Shale gas producing technologies are being introduced in the world regions with a natural gas shortage, liquefied natural gas terminals and storages are being built, and systems based on renewable energy sources are being developed. This article considers a variant of energy-efficient, financially low-cost and reliable coal-water suspensions technology of preparation and combustion or further transportation to consumers. Coal mines in the EU countries and in the north-eastern part of the PRC, as well as in some industrial regions of the Russian Federation, suspend operations due to unprofitability, development of main layers, or due to limit of CO₂ emissions into the atmosphere. The proposed technology takes into account the specific thermophysical properties of the coals and can be integrated into existing coal-fired power plants or operate as separate block boiler houses.

2. Prerequisites for the proposed technology development
The problem with burn-out of fuel (except for lean coals and anthracite), as a rule, does not arise in furnaces with flaring combustion of pulverized fuel. Previously, attempts were made to use in them a water-coal suspension - a mixture of coal dust and water with additives of surface active substances (surfactants). Water, being an ordinary ballast, reduced the conventional fuel combustion heat in proportion to its content in the mixture. With regard to brown coal, this is clearly demonstrated by the experiments on the TP-35 boiler conducted by UralVTI jointly with KirNIIE at the Mine-Kush combined heat and power plant (CHPP) [1]. Figure 1 shows the change in the dimensionless temperature and the degree of fuel burn out along the conventional flame length from the cut of the burners to the furnaces exit window. It can be seen from Figure 1 that the bulk of the fuel burns out to 90% in the horizontal section of the flame in front of the burners. The maximum temperature level of the flame develops here. On the vertical section of the combustion chamber, the flame is cooled to
fixed experimental value $T = T_{\text{ex}} = 1230$ K (in the furnace window at the flue gases outlet from the furnace, parameter $T_{\text{rel}} = T/T_{\text{ex}} = 1.0$; $a = 0.95$). When a pulverized suspension of coal dust with a maximum size of up to 350 $\mu$m with addition of water up to 50% and a surfactant, 1% (water-coal mixture 1, WCM-1) is fed into the furnace, the combustion pattern changes sharply: the flame temperature level in the ignition zone drops sharply. The maintenance of combustion in the experiments was carried out by lighting with diesel fuel in an amount of 7-12% for heat release.

The process of ignition and afterburning is greatly stretched, which leads to increased underburning at an integral value of $a = 0.82$ behind the furnace, heat loss with outgoing gases, reducing the boiler efficiency, additional losses for spraying.

At the same time, when analyzing the ash residue, it was found that the largest contribution to the integral values deviations of the burnout degree is made by the largest fractions with $R \geq 90$ $\mu$m, Figure 1(b). This also applies to dust combustion and incineration of the WCM. Fractions with $R < 90$ $\mu$m burn out in the furnace to 90 – 95%, and the isolated particles with $R \leq 40$ $\mu$m are burned almost completely.

Volatile substances present in the initial coal partially dissolve in the suspension water, partially retained in the dust component, as well as in pulverized coal flame, burn first with coke breeze [2].

WCM is crushed into drops when spraying. When drops heated in the furnace, evaporation of water vapor and volatile substances occurs, and coke particles included in drops composition are sintered, forming conglomerates, whose behavior in terms of oxidation and heat release differs little from the behavior of the dust particles in the flame and can be described by general mathematical dependencies. The calculation (WCM-2) for such dependences shows that the WCM-2 flame from particles with sizes $\leq 3$ $\mu$m already fits into the combustion process of ordinary coal, Figure 1. It is possible to make a forecast from here: the transition to a new generation suspension on re-grinded particles (WCM-2) will lead to an improvement in the combustion process and the technical and economic boiler performance in comparison with the same WCM-1 indicators.

A unique experience of separate and co-incineration of condensed sludge and coal dust on a powerful 200 MW boiler at the Belovskaya State District Power Plant (SDPP) was obtained in the power industry. Sludge is a mixture of water and fine dust with a size of up to 150-350 $\mu$m – obtained after hydrotransport of coal with the size of pieces up to 25 mm from the Inskaya coal mine to the coal storage of the Belovskaya SDPP. The main disadvantages of the technology are the frequent occurrence of large fragments of fuel $> 350$ $\mu$m in the nozzles and their clogging, as well as a decrease
in the efficiency of the boiler. Also at the Belovskaya SDPP in Kuzbass, there is possibility of obtaining highly concentrated water-coal suspensions (HCCWS) from coals of marks F and GF of Mokhovsky and Kolmogorov cuts of Kuzbass, which are a reserve source of raw materials for preparation of HCCWS with a complex of structural-rheological properties. With the appropriate selection of the granulometric composition and the introduction of plasticizers based on humic acids, it is possible to prepare 59 ... 61 % HCCWS with statutory indicators.

A similar experience was obtained on the 200 MW boiler of Novosibirsk CHPP-5, where they faced the same problem. A mixture with a particle size of up to 350 µm was fed through a 250 km pipeline, the mixture stratified and clogged the pipeline. The transition to a mixture with particle sizes of ≤ 3 µm should eliminate the problems of feeding and spraying, dramatically improving the combustion process. The ballast content of moisture should be compensated by the enrichment of the dust with the removal of the rock during the preparation of the mixture. Such complex cooking technology will ensure the efficiency of the existing boiler brought to the design value.

Thus, if one takes into account the accumulated experience of burning coal-water suspensions on industrial boilers, it is hardly possible to expect any qualitative transitions [3, 4]. In suspension, excess water is a conventional ballast, which reduces the specific combustion heat in proportion to its content in the mixture. For Kuznetsk coals with a heat of combustion of 22000 J / g, the mixture has a working heat of combustion of 12500 J / g. This is a very high indicator for coal and mixtures of brown coal. It is quite possible to organize joint enrichment and formation of a mixture with sizes of coal particles ≤ 3 microns.

Joint enrichment and preparation of water-coal mixture – a subject area which will provide an increase in the mixture combustion heat due to the removal of excess rock; it should be developed before industrial introduction [4]. At present, scientists have made a significant contribution to research on fuel preparation, improving its rheological properties, the possibility of transportation while maintaining the necessary thermophysical characteristics of the fuel [5].

3. Structure of the heat-and-power complex

Developed and existing energy technology complexes for the preparation of the WCM can be represented in the form of a structural diagram, shown in Figure 2.

![Figure 2. Structural diagram of energy-technological complex for preparation of WCM.](image)

In the WCM preparation part, the complex includes [2, 5] a coal-water mash pump, a pump for pumping the finished suspension, a coal grinding mill or hydrodynamic cavitation apparatus, a dispersant, a surfactant additive dispenser, filter systems or dewatering systems. In the combustion of the prepared WCM, the complex includes [1, 3, 4] a combined burner for combustion of WCM,
upgraded for combustion of a WCM boiler, auxiliary equipment of the boiler unit, namely a fan, a smoke exhaust, feed pump, if necessary circulating and booster pumps, valves, regulators, bypass pipelines.

Control of all complex systems and their operation diagnostics can be implemented on the basis of a multi-zone controller (Multi-zone integrating regulator, hereinafter MR), which refers to an intelligent system with the possibility of self-diagnosis and self-reservation [6]. Also, the basic control algorithms can be implemented with the use of neural networks, selecting the optimal strategy for burning the WCM depending on the known coal parameters (ash content, caking) and the proportion of water content. The neural network can regulate the supply of fuel and oxidant to obtain optimal parameters of the flame and eliminate underburning. This will not only have a favorable effect on the boiler efficiency, but will also affect CO₂ emissions. Thus, neural networks not only use unused potential, but also improve the state of the environment in the future.

Speaking about the automation of the technological process, as a rule, they imply the realization of all the ones shown in Figure 2 systems based on a regulated electric drive. A regulated electric drive, as a rule [7], is more economical than any uncontrolled system.

4. Structure of electric drive of pumping units

Let us consider an example of an electric drive of pumping units for pumping coal-water mash, suspensions, etc. It contains a control system (CS) – for example, a thyristor voltage regulator (TVR), an electric motor (EM) – for example, an asynchronous and actuating mechanism (M) – a pump, as well as sensors (S) monitoring operations and conditions CS, EM and M (Figure 3). Sensors or a complex of selective protectors can, for example, issue information: about activation of overcurrent protection and / or time current protection in the circuit; about presence of mains voltage; about the overheating of bearings, about an increase / decrease of pressure at the outlet, etc.

In addition, extra pump can be included in the system in addition to the main channel to provide a given pressure, for example, a boosting pump of lower power with its separate control. Thus, the electric drive of pumping units consists of several parallel channels, these units operating on a common pipeline and providing a given pressure. The structure can also provide a backup channel, which ensures reliable system operation in case of failure of the main one.

5. Control system for a group of electric drives of pumps based on a multi-zone regulator

Simultaneous operation of the main and additional channels with the specified characteristics (pressure, velocity, etc.) or automatic transition to a reserve channel can be realized by implementing a drive control system for pumps based on a MR. The multi-zone regulator refers to pulse systems [8] with frequency-pulse-width modulation of the output signal.

As practice shows [6] similar structures are characterized by simplicity, reliability and high economic indicators.

An example of a structure based on MR is shown in Figure 4. The multi-zone regulator consists of an input source (U₀), adders ∑₁ and ∑₂, an integrator with integration time constant Tᵢ and groups of relay elements (RE). In general, the number of RE can be even or odd. In Figure 4, an option is considered for four RE. In addition, the system in Figure 4 includes "k-1" parallel channels. Each of them consists of a series-connected thyristor voltage regulator (TVR), an electric motor, for example, asynchronous (AM) and pump (P).

The pumps operate on a common outflow line. In such structure, for example, it can be states that the first and second pumps P₁ and P₂, working together or alternately provide a predetermined outlet pressure, and the last (P₃) serves as a backup function.

Depending on the magnitude and sign of input signal U₀, the MR leads from one zone to another, which guarantees a certain state of the output signals of all relay elements RE₁-RE₄. The maximum signal at the output of each RE can be taken as the logic level "1" or the "Start" command for relevant channel TVR-AM-P. Similarly, minimum output signal RE is equivalent to the logical "0" level or the "Stop" command.
If the number of RE is odd, then their output is directly connected to the input of the corresponding TVR. If the number of RE is even «k≥4» (Figure 4), then one of the channels is switched on from the "k-1"-bit memory register (RG), which works in a complete set with a digital comparator (C) and a univibrator (U).

Entering additional blocks when implementing an MR with an even number of RE is associated with the following problem. When the MR moves from one modulation zone to another, one or more RE may be triggered. This leads to a short-term (false) start of the corresponding electric motor, which in reality should be in the off state. The operation accuracy in such system is achieved due to blocking the TVR control inputs until MR does complete the transient process. Those while in the MR carries the transition from one modulation zone to another. In this case, during the transient process, the code state of the previous modulation zone is stored in the memory register. Only after the MR enters into the stable oscillation mode, the state of the group of electric drives changes, when the code state of the group «k-1»-relay elements corresponds to the steady state of the required modulation zone.

For example: if as an input, MR signal $U_0$ supplets information from the sensor about the pressure in the output line, then a closed structure is realized. Thus, it is possible to switch on / off the required number of simultaneously running pumps and adjust the parameter (pressure, velocity, etc.) with specified accuracy. This will certainly affect the energy efficiency of the entire system. In Figure 4, sensors and / or a complex of selective protections are not shown (in accordance with the structure in Figure 3). Adding them to the system will automatically put into operation a backup complex of protections in case of malfunctions in one of the nodes of the main channel, consisting of TVR-AM-P. The uninterrupted operation of each elements and the system as a whole will also affect the economic component, the quality of water-coal suspensions preparation and the efficiency of the entire complex.

The structure based on MR can be offered for ventilation systems, smoke removal, and also those systems that contain several parallel channels, including backup channels, in accordance with the structure in Figure 2.
6. Application of the neural network algorithm

The used control algorithms and diagnostics of the heat energy system can be implemented using neural network algorithms. With well-established work of the neural network, the reliability of the energy technology complex for the preparation and combustion of the WCM increases, the operating characteristics of the boiler improve the influence on the ecology [9, 10]. In addition, accounting for the characteristics of combustible fuels, such as ash and caking, will allow one to select effective parameters of the flame not only from the point of view of the received heat, but also from the point of view of the sinterability of water-coal formations. This will reduce the sticking and scorching of the VUS to the boiler walls and nozzles and will increase the service life of the boiler unit.

7. Conclusion

It is shown that an increase in the efficiency of existing energy technology complexes for the preparation and combustion of water-coal suspensions is possible with flame utilization in boiler units at the site of their production. The industrial introduction of block energy complexes should be accompanied by automation of technological processes.

The electric drive of the main units of the energy technology complex for the preparation and burning of water-coal suspensions is recommended to be regulated. Its implementation on the basis of a multi-zone regulator will additionally improve the quality of regulation of specified parameters and effectively solve reliability issues, in particular those related to automatic diagnostics and reservations. Implementation of neural network algorithms will allow one to develop and to consolidate this effect, further increasing the reliability and economy of the system.

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