Modeling an automated management system of technological processes in public energetics

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Abstract. The article presents an algorithm for managing the fluidized bed boiler during solid fuel combustion at the enterprises of the fuel and energy complex. The review of technological features of fuel combustion in low-power boilers of high-temperature fluidized bed is performed. The calculated parameters of the furnace processes in transient operating modes are modeled. A program for managing calculated parameters in dynamic modes from the operator's graphical panel has been developed, which is used as a training model in the educational process of training thermal-power and sanitary engineers.

1. Introduction

The training of qualified personnel for the Russian energy sector is one of the most acute problems faced by employers today. The industry lacks qualified engineers, on the one hand, and modern teaching methods and models, on the other. The use of training models in the educational process allows future engineers to get both the skill of settlement-research and design activities, and experience in implementing production and technological processes.

Worldwide training trends for power engineers are also aimed at strengthening the natural link between teaching and practical research [1]. In this regard, it should be noted that engineering education by its nature is a costly program in university environments [2]. Therefore, the use of simulation is not only a good tool to improve the quality of training of engineers, but also a peculiar way to save budget costs for the organization of the educational process.

Today, the Military Institute (Engineering) conducts research on the operation of low-power boilers (1-3 MW) with VTKS furnaces by combustion of solid fuel in static and dynamic modes of operation [3-5]. As a result, data were obtained that the program of modeling and operation of the automated management system in boiler water provides the optimum temperature and concentration of combustible substances in the boiler furnace. Calculation of the main parameters of transient combustion processes in low-power boilers is performed in management and modeling units. This software is used in the educational process to prepare students of the thermal-energy and sanitary-technical specialties for calculating the main indicators of transient processes, as well as for selecting control regulators.

2. Materials and methods

Integrated automation system is a prerequisite for the smooth functioning of combustion processes in low-power boilers with a fluidized bed. To identify the functional and technological features of the
operation of automatic control systems, it is necessary to characterize the research objects themselves, which can be divided into 3 groups [6]:

- Low-power boiler units with furnaces of a high-temperature fluidized bed (VTKS).
- Low-power boiler units with furnaces of a low-temperature fluidized bed (NTKS).
- Combined power plants for the joint generation of thermal and electric energy with active boilers of utilizing a fluidized bed.

Let us consider in detail the issue of automation of solid fuel combustion processes in low-power boilers with a fluidized bed on a narrow inclined movable grate.

This technology is widely used in public energetics and is best known as the high-temperature (circulating) fluidized bed [7]. In the VTKS there are no inert materials, the bed is formed by the solid fuel itself. A characteristic feature is the use of zone primary blast with different pressure of the air mixture in each blast zone. The main management parameters are the temperature of the fluidized bed, the consumption of fuel, air, recirculation gases, rarefaction in the boiler furnace, moreover, it is additionally necessary to control the pressure of the primary and secondary air or air mixture in each blast zone [8]. A distinctive feature of boilers with VTKS is an increased combustion temperature in the bed of 1100 ... 1250 °C.

One of the main issues in regulating the fuel combustion process is ensuring the optimal fuel / air ratio, which significantly increases the efficiency of fuel combustion. The separation of air into primary and secondary does not lead to the desired increase in efficiency, moreover, a sharp change in the pressure of the primary air can lead either to an excessive increase in the height of the fluidized bed (FB) or to the damping of the combustion process. An important issue is the control and maintenance of the temperature of the fluidized bed at a given level. The difficulty lies in the fact that in some cases the temperature does not adequately respond to disturbing influences, such as changes in moisture, ash, and coarseness of the pieces of fuel, which leads to its sharp increase or decrease. [9, 10].

3. Results and discussion
Regulation and calculation of the main parameters of transient processes when applying disturbing effects in low-power boilers with a fluidized bed is performed in the developed automated system for monitoring the combustion of solid fuels. The calculation is performed in the control and simulation blocks.

The task of the management unit is to implement the boiler mode map and to form the main control influences: supply of fuel, air and recirculation gases.

In the modeling block, the integration of differential equations describing the dynamics of combustion processes is performed.

These calculated parameters provide automated transient control using the example of the VTKS “KVP-1.74-VTKS” coal-fired boiler unit controlled via a programmable logic controller (PLC) from the graphic operator panel.

The software for modeling and operation of the control system of the first block includes:

- OMRON PLC CJ2M, with CX-Programmer software from the CX-One toolkit.
- A program for displaying and controlling combustion processes for a programmable graphic panel developed using the EasyBuilder Pro tool program, where it is defined: control variables of the combustion process (fuel, air and recirculation gases) and dynamic characteristics of actuators.

In the modeling block, the following actions are implemented: new optimal values of the temperature of the fluidized bed are determined by time and concentration of fuel in the boiler furnace by integrating the values of the system of differential equations numerically. If the obtained parameters do not coincide with the calculated and experimental values obtained in experimental studies and implemented in the
boiler mode map, a correction coefficient is used that depends on the concentration of fuel in the boiler furnace and adjusts the control system.

The main control influence when modeling transient combustion processes of a high-temperature fluidized bed coal boiler is its load capacity in five modes, set as a percentage of the rated load.

The combustion process is controlled by the boiler mode map (table 1).

Table 1. Fragment of the mode map of the VTKS boiler.

| № | Name of value                  | Designation | Dimension | Mode №1 | Mode №2 | Mode №3 | Mode №4 | Mode №5 |
|---|--------------------------------|-------------|-----------|---------|---------|---------|---------|---------|
| 1 | Boiler capacity load           | -           | %         | 40      | 60      | 80      | 100     | 120     |
| 2 | Recirculation gas consumption  | G           | m³/hour   | 180     | 270     | 360     | 450     | 540     |
| 3 | Air consumption                | W           | m³/hour   | 1021    | 1531    | 2042    | 2553    | 3060    |
| 4 | Fuel consumption               | Bset        | kg/hour   | 135.2   | 202.8   | 270.4   | 340     | 400     |

The mode map data is entered into the PLC in tabular form. Numerical values for the formation of control variables of the combustion process between the set points of modes are determined using the nonlinear function of piecewise linear approximation.

The control variables of the combustion process are fed to relay controllers, which, taking into account the dynamic characteristics of the actuators, determine the flow of components of the combustion processes: fuel, air and recirculation gases.

The dynamic characteristics of actuators are set by the velocity of change (rate) of the supply of components of the furnace process: the rate of increase / decrease of fuel supply $V_t$ (determined by the rate of filling of the fuel supply path), the rate of increase / decrease of air consumption $W_t$ or consumption of recirculation gases $G_t$ (determined by the velocity of opening / closing of guide vanes and gates).

Figure 1. A fragment of the control algorithm of furnace processes.
For stable operation, the control hysteresis is determined by the set rate and reduced to the integration step $\Delta t$.

Figure 1 shows a fragment of the control algorithm, where:

$B_{set}[n]$ – set value of the fuel supply, determined by the mode map;

$B_{cur}[n]$ and $B_{cur}[n−1]$ – fuel supply value at the current and previous integration step.

The algorithm for controlling the supply of air and gas recirculation looks similar, where:

$W_{set}[n]$ – set value of the air supply, determined by the mode map, [m3/hour];

$W_{cur}[n]$ and $W_{cur}[n−1]$ – air supply value at the current and previous integration step, [m3/hour];

$G_{set}[n]$ and $G_{cur}[n−1]$ – value of recirculation gas supply at the current and previous integration step, [m3/hour].

Modeling of furnace processes of a coal boiler implements numerical integration of a system of two differential equations (1-3).

$$
\begin{align*}
    z[n] &= \frac{\Delta t}{V_{P_k}} B[n] + \left(1 - \frac{\Delta t S_{ij}}{V_{P_k}}\right) z[n-1] \\
    t[n] &= \frac{\Delta t V_{S} Q_{rij}}{M C_m} z[n] + \left(1 - \frac{\Delta t F_C C_{g} g [n]}{M C_m} - \frac{\Delta t F_{P_k} F_k}{M C_m}\right) t[n-1] \\
    B[n] &= B_{mek}[n]; \quad w[n] = \frac{w_{mek}[n] + G_{mek}[n]}{F}
\end{align*}
$$

where $z[n]$ - concentration of fuel at time $t$; $t[n]$ - temperature of the fluidized bed at time $t$; $M$ - mass of the fluidized bed; $V$ - volume of the fluidized bed; $\rho_k$ - density of coke particles; $C_m$, $C_g$ - specific heat capacity of the bed material, combustion products; $Q_{rij}$ - fuel calorific value; $F$ - cross-sectional area; $F_{P_k}$ - heat transfer surfaces; $k_p$ - heat transfer coefficient; $S$ - specific surface area of reacting coke particles; $w$ - free section velocity of combustion products; $B$ - fuel consumption, $j$ - specific carbon flux during its reaction with oxygen, $G$ - recirculation gas velocity.

Numerical integration is performed in increments of $\Delta t = 0.1$ s.

To satisfy the conditions for finding the temperature of the fluidized bed at the given points of the mode map (see table 2), an additional coefficient $K_z$ with automatic correction (table 3) is introduced into the model of furnace processes depending on the value of the concentration of combustible $Z[n]$. With the correction coefficient $K_z$, the expression for the numerical integration of the temperature of the he fluidized bed has the form:

$$
\begin{align*}
    t[n] &= \frac{\Delta t V_{S} Q_{rij}}{M C_m} z[n] + \left(1 - \frac{\Delta t F_C C_{g} g [n]}{M C_m} - \frac{\Delta t k_p F_k}{M C_m}\right) t[n-1] \\
    B[n] &= B_{mek}[n]; \quad w[n] = \frac{w_{mek}[n] + G_{mek}[n]}{F}
\end{align*}
$$

### Table 2.

| №     | Name of value                        | Designation | Dimension | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 |
|-------|--------------------------------------|-------------|-----------|--------|--------|--------|--------|--------|
| 1     | Boiler capacity load                 | -           | %         | 40     | 60     | 80     | 100    | 120    |
| 2     | Boiler heating capacity              | Qpos        | Gcal/h    | 0.60   | 0.90   | 1.20   | 1.50   | 1.8    |
| 3     | Temperature in the boiler furnace    | t           | °C        | 1017   | 1103   | 1175   | 1215   | 1250   |

| №     | Name of value                        | Designation | Corrective dependence |
|-------|--------------------------------------|-------------|-----------------------|
| 1     | Concentration of combustible         | $Z[n]$      | 0.0228 0.0340 0.0453 0.0570 0.0670 |
The program for displaying and controlling the transient process from the graphic operator panel consists of 14 windows, including information display tools, information input tools, tools for changing modeling modes and switching to other windows.

This program runs continuously when it is downloaded to the Weintek eMT3120 operator panel and for 10 minutes when it is launched in interactive modeling mode from the EasyBuilder Pro tool program.

In the main menu window, there are five keys to go to the model parameter and management settings windows and seven keys to go to the mode setting window and the current process parameters window (figure 2).

For the convenience of analysis in the interactive modeling mode, modeling scaling has been introduced (acceleration by 5 times).

In the settings window of the mode map, the values of the controlled parameters of the components in the steady-state modes of the furnace process are set: fuel supply, air consumption and recirculation gas consumption (figure 3).

The management settings window is designed to set the dynamic characteristics of actuators that provide fuel, air and recirculation gases; it is also possible to model the set value of the disturbing effect with a change in the air-gas mixture consumption.

The model also provides: a setup window and an automatic correction window. In the model settings window, the changing values of the parameters and differential equations are entered, which are used for modeling the transition process. An automatic model correction window is intended for setting the
correction type and specifying the values of the adjusted parameters at the set points of the mode map. Such correction is necessary to achieve the required fluidized bed temperature at the set points of the mode map when the load changes over the entire range.

The boiler load setting window (figure 4) has digital indicators showing the current load and the current value of the main parameters: fuel supply, air and recirculation gases consumption, fluidized bed temperature.

![Figure 4. Boiler load setting window.](image)

The window for displaying changes in the fuel and air-gas mixture is presented in figure 5.

![Figure 5. Window displaying a graph of the change in fuel and air-gas mixture over time.](image)

The results of the management process and modeling of furnace processes as a function of time are recorded in graphical form. The curved line of the time dependence of the current parameter is supplemented by a digital indicator showing the current value. Figure 6 in the presented windows shows the transient process of interactive modeling with scaling the time of the fluidized bed temperature when the load changes from 80% to 100%, with a further change in the installed load from 100% to 120%.
Figure 6. Window displaying a graph of the fluidized bed temperature over time.

The results of the management process and modeling of combustion processes as a function of time show satisfactory convergence with the experimental data obtained by conducting studies of dynamic modes on the VTKS "KVP-1.74 VTKS" boiler at loads from 50 to 120% [11].

4. Conclusion
Thus, the use of this automated management system can improve the stability and quality of operation of low-power solid fuel boilers with a fluidized bed, which increases their technical, economic and environmental indicators. The developed software package makes it possible to train specialists to model transients and gain skills in managing this type of boilers during combustion of various types of solid fuel at the working experimental facilities of the institute's training base.

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