Justification for effectiveness of stepwise heat supply during preliminary thermal processing of solid organic fuel

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Abstract. This paper presents the practical justification of the efficiency of the organization of step heat supply in the process of pre-heat treatment of solid organic fuel. Two options were considered heat training: at a constant temperature and with a step-heating.

1. Introduction

Improving the technology of production and consumption of energy produced by solid organic fuels is given considerable attention in the energy sector. Existing problems of energy use of coals can be largely solved if carbon dust is subjected to thermochemical processing before burning. The good flammability of thermal processing products, their high caloric value and reactivity open up wide possibilities for the application of thermal pre-processing of coal before burning in thermal power plants. However, the issues of the influence of regimes and methods for realizing the thermal preparation of fuel on indicators of the energy efficiency of boiler units, the reliability of their operation and environmental safety require further research.

2. Methods and data

The rate of thermochemical conversion of coal dust (for example, due to thermal destruction and partial gasification of the solid non-volatile residue) during its thermal preparation depends on the average process temperature, which can be increased by the stepwise supply of combustion products to the coal dust stream. It has been experimentally proved that a much higher thermal decomposition rate of coal is achieved if the fuel continues to be heated in this process. Data presented in [1] indicate that the coal which is being heated during the thermal treatment from 600 to 700 °C, has twice the reactivity as compared with maintaining a constant temperature of 700 °C. It is believed that when thermal decomposition is activated by an increase in temperature, some intermediate compounds which substantially change the reaction mechanism in comparison with the conditions available at a constant temperature are being formed.

In this article, for a practical justification of the effectiveness of the organization of the stepwise heat supply in the process of preliminary thermal processing of solid organic fuel, a comparison of two possible options for realizing this process is made. For both variants, a limitation is made on the maximum temperature of coal dust after mixing with high-temperature combustion products.

In the first, traditional method (Fig. 1, a), all coal dust is mixed immediately with all combustion products. To fulfill the condition to limit the temperature of the coal, some of the recirculation gases which have the temperature of the gases leaving the boiler unit (flue gases) are added to high-temperature combustion products. In the second variant (Fig. 1, b), the high-temperature combustion products are divided into several parts, which are mixed stepwise with the coal dust flow in such a way that the temperature in any point of the process does not exceed the specified maximum value.
Figure 1. Calculation schemes of different ways of organizing the preliminary thermal processing of pulverized solid fuel: \( a \) – with the input of the entire amount of heat at the beginning of the process; \( b \) – with stepwise heat supply; 1 – combustion chamber for burning part of a fuel in order to obtain high-temperature combustion products; 2 – the mixer; 3 – thermal processing chamber; 4 – the supply of part of the fuel to produce high-temperature combustion products; 5 – supply of the main part of fuel for thermal processing; 6 - supply of recirculation gases; 7 - air supply; 8 - the path of combustion products for the stepwise heat supply; 9 - stages of thermochemical treatment; 10 - withdrawal of products of thermochemical transformation of coal.

The rates of chemical reactions in the thermal preparation of solid fuels, using the example of coal mined in Borodinsky open pit of Kansk-Achinsk basin (hereinafter Borodinsky coal) are described by the following equations

\[
W_{\text{H}_2\text{O}} = \frac{3.44 \cdot 10^5}{T_{\text{tp}}} C_{\text{H}_2\text{O}} \exp \left( \frac{16000}{T_{\text{tp}}} \right); \quad W_{\text{CO}_2} = \frac{9.0 \cdot 10^5}{T_{\text{tp}}} C_{\text{CO}_2} \exp \left( -\frac{17500}{T_{\text{tp}}} \right),
\]

where \( W_{\text{H}_2\text{O}} \), \( W_{\text{CO}_2} \) – the reaction rate of water vapor and carbon dioxide with a non-volatile (coke) fuel residue, respectively, kg/(m²·s); \( C_{\text{H}_2\text{O}}, C_{\text{CO}_2} \) – concentration of water vapor and carbon dioxide, respectively, kg/Nm³; \( T_{\text{tp}} \) – temperature of the thermal processing, K.

The effectiveness of the compared options is determined by the ratio of the rates of reactions occurring during the thermal processing of the fuel.

For water vapor:

\[
\frac{W'_{\text{H}_2\text{O}}}{W_{\text{H}_2\text{O}}} = \frac{T_{\text{tp}}^2}{T_{\text{tp}}^1} \exp \left[ -\frac{16000(T_{\text{tp}}^2 - T_{\text{tp}}^1)}{T_{\text{tp}}^1 \cdot T_{\text{tp}}^2} \right],
\]
where index 1 refers to the variant of mixing all combustion products with coal dust at the beginning of the process (Fig. 1, a), and index 2 to the stepwise supply of combustion products (Fig. 1, b).

The temperature of the process of thermal preparation of pulverized solid organic fuels is defined as the arithmetic mean of the temperature of the mixture at the inlet and outlet of each design stage of thermal processing. Denoting the temperature of the heterogeneous mixture at the inlet to the heat treatment unit (the stage of the heat treatment device) as \( t' \), we determine the temperature of the heterogeneous mixture at the outlet of the device (the stage of the thermal preparation device) – \( t^* \) by drawing up the heat balance of the thermal preparation scheme, taking into account the thermal decomposition of the fuel and the chemical mechanism of reaction of solid non-volatile residues with high-temperature gaseous products of combustion of a part of fuel.

Let us determine the temperature \( t^* \) during thermochemical treatment of pulverized solid organic fuel by high-moisture gaseous products:

\[
t^* = \frac{k}{n} G_{\text{coal}} c'_{\text{coal}} t' + \frac{k-1}{n} G_{\text{coal}} c_{\text{coal}}^* + G_{\text{g}} c_{\text{g}}^* t' + \frac{k-1}{n} G_{\text{coa}} c_{\text{coa}}^* + G_{\text{g}} c_{\text{g}}^* + G_{\text{coa}} c_{\text{coa}}^* - (C_{\text{CO}_2} c_{\text{CO}_2}^* - G_{\text{CO}} c_{\text{CO}}^*) (k + 1)
\]

\[
= \frac{k-1}{n} G_{\text{coal}} c_{\text{coal}}^* + G_{\text{g}} c_{\text{g}}^* + G_{\text{coa}} c_{\text{coa}}^* - (C_{\text{CO}_2} c_{\text{CO}_2}^* - G_{\text{CO}} c_{\text{CO}}^*) (k + 1)
\]

where \( n \) is the number of stages of preliminary thermal processing of solid organic fuel; \( k \) is the index of the calculated step; \( G_{\text{coal}}, G_{\text{coa}} \), \( G_{\text{g}}, G_{\text{co}}, G_{\text{pg}} \) – consumption of coal, combustion products needed to increase the temperature of the heterogeneous mixture ahead of the \((k + 1)\) stage, respectively, kJ/(kg·K); \( c'_{\text{coal}}, c_{\text{g}}, c_{\text{co},}, c_{\text{co}}, c_{\text{pg}} \) – the heat capacity of coal, gases behind the combustion chamber, flue gases, carbon dioxide, carbon monoxide and pyrolysis gas at temperature \( t' \), respectively, kJ/(kg·K); \( c_{\text{coal}}^*, c_{\text{g}}^*, c_{\text{co},}^*, c_{\text{co}}^*, c_{\text{pg}}^* \) – the heat capacity of coal, flue gases, carbon dioxide, carbon monoxide and pyrolysis gas at temperature \( t^* \), respectively, kJ/(kg·K); \( Q_1, Q_2 \) – thermal effects of thermochemical transformation of coal, kW; \( g_{wv} \) – amount of water vapor, kg/kg; \( \psi \) – weight consumption of coal in the mixer in fractions of the total amount of coal fed into the combustion chamber; \( V_0^h \) – theoretical volume of gaseous combustion products per mass unit of fuel, m³/kg.

Fig. 2 shows the change in the temperature of the process of preliminary thermal processing of solid organic fuel, depending on the change in the mass of the reacted fuel, provided that the maximum temperature of the heterogeneous mixture is limited.
Figure 2. Dependence of the temperature of the process of preliminary thermal processing of solid organic fuel ($T_{tp}$, °C) on the mass of the reacted substance ($m$, in shares) at a maximum temperature of 1000 °C: 1 – with the input of the entire amount of heat at the beginning of the process; 2 – stepwise supply of combustion products in equal proportions; 3 – stepwise supply of combustion products in an unequal ratio (incremental).

It should be noted that the stepwise supply of heat during the thermal processing of coal dust increases the rate of thermal decomposition and chemical reaction of a non-volatile residue with water vapor and carbon dioxide. So, with three stages of heat input and thermochemical conversion of 50% of the organic mass of fuel, the process speed increases by 2.5-2.8 times for the Kuznetsk and Kansk-Achinsk coals. In this case, the efficiency of the stepwise heat input will be even higher if the process temperature at each stage of heat treatment is not kept constant but increased as the step number increases (line 3 in Fig. 2). It is proposed to maintain the process temperature at 400 °C at the first stage, 600 °C at the second and 800 °C at the third. Such organization of the thermal processing ensures its greatest non-isothermality, which makes it possible to increase the efficiency of thermal treatment by another 15-20%, reduce fuel costs for obtaining high-temperature combustion products, and rationally fulfill the scheme of practical implementation of the process, taking into account the physicochemical properties of the fuel. It is assumed that in the first stage the process of deep drying of the fuel takes place with the release of ballast volatiles (mainly carbon dioxide). In the second stage, thermal decomposition of fuel is carried out, accompanied by the release of low-calorie gaseous volatile substances (carbon monoxide, methane, hydrogen, etc.). In the third stage of thermal processing, a deep destruction of fuel occurs, with the release of the bulk of high-calorific gas-vapor components (resins, etc.).

To determine the time of the process of thermal treatment of coal dust, we rewrite (1) in the following form

$$W_{H_2O} = \frac{1}{T_{tp}} \frac{dC_{H_2O}}{d\tau} \quad ; \quad W_{CO_2} = \frac{1}{T_{tp}} \frac{dC_{CO_2}}{d\tau}. \quad (6)$$

From where do we find the time of the processes
Expressions (4), (5), (7) and (8) allow calculating the dynamics of the process of thermal preparation of solid organic fuel. Fig. 3 presents the results of calculating the dynamics of thermal preparation process of Borodinsky coal using a stepwise supply of combustion products to the mixing chamber.

Figure 3. Calculated dynamics of the process of preliminary thermal processing of solid organic fuel at a maximum temperature of 1000 °C.

Calculations show that the residence time of solid fuel in the gas generator depends on the number of stages of supply of combustion products. In this case, the following universal dependence of the determination of the thermal processing time on the number of heat input stages is obtained

\[ \frac{\tau_1 \cdot n_2}{n_1 \cdot \tau_2} = \frac{\tau_2 \cdot n_3}{n_2 \cdot \tau_3} = \ldots = \frac{\tau_i \cdot n_{i+1}}{n_i \cdot \tau_{i+1}}, \]

where \( \tau_1, \tau_2, \tau_3, \ldots, \tau_i, \tau_{i+1} \) – residence time of solid fuel in the thermal processing device, s; \( n_1, n_2, n_3, \ldots, n_i, n_{i+1} \) – number of heat input stages.
3. Results

Fig. 4 depicts a patented scheme for implementing the method and devices for organizing the stepwise thermal preparation of pulverized fuel for combustion in a boiler unit of a thermal power plant [2].

The implementation of the method for regulating the combustion regime of a steam generating unit is carried out as follows. The pulverized slurry from the dust source 8 is fed sequentially to the thermal preparation devices 5, 6 and 7 through the regulators 11-13 (which allow varying the residence time and the amount of coal dust in each of the devices) and further to the main burner 2.

From the source 10, air is supplied to each stage of the thermal processing in the devices 5, 6 and 7 to control the temperature in each of the devices, as well as to the main (2) and discharge (3, 4) burners. The heat-treated coal dust leaving the device 5 enters the cyclone 16, where coal dust is separated from the steam-gas thermal processing products. From the cyclone 16, coal dust is fed to the thermal preparation device 6. From the device 6, the heat-treated coal dust, after being separated with the vapor-gas products in the cyclone 17, enters the thermal preparation device 7.

![Diagram of the method of implementation of multistage preliminary thermal preparation of coal dust before burning](image)

Figure 4. The method of implementation of multistage preliminary thermal preparation of coal dust before burning: 1 – steam-generator furnace; 2 – main burner; 3, 4 – discharge burners; 5-7 – thermal processing devices; 8 – coal dust source; 9 – thermal coal bunker; 10 – air source; 11-13 – automatic regulators of the supply of coal dust in the thermal preparation devices; 14 – regulator of the flow rate of the thermal coal into the main burner; 15-18 – dust cyclones; 19 – flue gas channel; 20 – mill fan; 21 – air ejector

The heat-treated coal dust is fed into the main burner 2 through the regulator 14 from the thermal coal bunker 9, into which coal dust is being supplied from the cyclone 18, connected to the thermal preparation device 7. All regulators are connected to the control device, which in its turn is connected with the installation of a complex thermal analysis (CTA) which analyses coal dust from collectors installed on the coal dust supply line from source 8 and after devices 5, 6, 7. Thermal analyzer also examines gaseous products of heat treatment of coal from each stage of heat treatment. Dust and gas intakes are necessary for the experimental determination of the necessary temperature-time regime for the treatment of coal dust in devices for preliminary fuel pre-processing. The control device is also connected to a device for visual indication of current information.
Each stage of the coal dust thermal preparation process is carried out in independent devices, the task of which is to organize the process of fuel destruction, which provides the necessary level of drying and thermal decomposition of coal, depending on the quality of the initial fuel and the operating mode of the steam generating unit [3]. Thus, the first stage is carried out in the thermal preparation device 5, the second in the device 6, the third in the device 7. In the device 5, predominantly moisture and ballast volatile components (CO₂) are being evaporated from the fuel, which is ensured by the necessary temperature level (350-400 °C) and time (0.5-0.6 s) thermal processing. Control over the completeness of moisture evaporation from the fuel is carried out with the help of a complex thermal analysis unit.

In device 6, a higher temperature is maintained, which is 600-650 °C with a thermal processing time of up to 0.8-1 s to perform a deeper destruction of the fuel, with the rupture of the most labile chemical bonds, accompanied by the release of predominantly ballast (CO₂) and low-calorie (CO) volatile gaseous components.

In the thermal preparation device 7, where an even higher temperature of coal dust treatment is maintained – 800-850 °C, a deep decomposition of coal occurs accompanied by the emission of gaseous volatile components (CO, H₂, CH₄ etc.) at a processing time of 0.8-1 s. The resulting vapor-gas volatile components from the thermal preparation devices 5, 6 and 7 through the cyclones 16, 17, 18, respectively, are discharged via the flue gas channel 19 to the cyclone 15, from which they are fed to the discharge burner 4 by means of the mill fan 20.

4. Conclusion

The required temperature level of the coal dust preparation process at each stage is achieved by burning a part of the fuel with air dosed individually through regulators whose operating mode is set by the regulating device based on the data of the complex thermal analysis instrument [4]. Thus, the organization of a three-stage thermal preparation of fuel before combustion, in which the quantitative and qualitative characteristics of steam-gas and non-volatile coal preparation products are controlled with subsequent and also stepwise regulation of the ratio of fuel and air, makes it possible to increase the efficiency of the preliminary thermal preparation of coal before combustion, the thermal coal proportion and to provide the opportunity to regulate the thermal preparation process depending on the quality of the initial fuel.

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