A comprehensive study of combustion products generated from pulverized peat combustion in the furnace of BKZ-210-140F steam boiler

V A Kuzmin and I A Zagrai
Vyatka State University
Russia, 610000 Kirov, Moskovskaya, 36

Abstract. The experimental and theoretical study of combustion products has been carried out for the conditions of pulverized peat combustion in BKZ-210-140F steam boiler. Sampling has been performed in different parts of the boiler system in order to determine the chemical composition, radiative properties and dispersity of slag and ash particles. The chemical composition of particles was determined using the method of x-ray fluorescence analysis. Shapes and sizes of the particles were determined by means of electron scanning microscopy. The histograms and the particle size distribution functions were computed. The calculation of components of the gaseous phase was based on the combustion characteristics of the original fuel. The software package of calculation of thermal radiation of combustion products from peat combustion was used to simulate emission characteristics (flux densities and emissivity factors). The dependence of emission characteristics on the temperature level and on the wavelength has been defined. On the basis of the analysis of emission characteristics the authors give some recommendations how to determine the temperature of peat combustion products in the furnace of BKZ-210-140F steam boiler. The findings can be used to measure the combustion products temperature, support temperature control in peat combustion and solve the problem of boiler furnace slagging.

1. Introduction

Peat is a widespread mineral in Russia, and its reserves across the country are inferior only to coal reserves. More than 40 % of the world's peat reserves are concentrated in Russia, but it is inferior to other countries (Finland and Ireland) by the rate of production [1].

Co-combustion of peat and another types of fuel (woody biomass, coal, natural gas, fuel oil, etc.) [2−5] leads positive effects in solving operational problems inside existing boilers. For example, burning peat together with wood helps to control the combustion process and reduce the high-temperature corrosion of heat exchangers [2, 3]. Co-burning of coal and peat fuel granules does not lead to ashes agglomeration and reduces emission of SO₂ and CO₂ from existing coal-fired power plants and local boilers [4].

One of the main directions of the state energy policy of Russia is to increase the energy efficiency of power plants using local fuel resources. Peat is produced mostly in remote areas where there is a chronic lack of industrial jobs. At present, ZAO VyatkaTorf (Kirov region) [6] is the largest peat-extracting enterprise in Russia. It accounts for approximately 50 % of peat extraction in the country. On the territory of the Kirov region, peat is mined at 4 production sites: Dymny (Svetlopolyansk settlement of Verkhinekamsky district), Pishchalsky (Mirny settlement of Orichevsky district),
Karinsky (Oktyabrsky settlement of Slobodskoy district), Gorokhovsky (Komsomolsky settlement of Kotel'inchensky district).

The main deliveries of extracted raw materials are carried out to Kirovskaya CHPP-4 of OAO Territorial Generation Company №5, which consumes about 50 % of peat in Russia, intended for the needs of heat and electric power industries. At this enterprise, 10 steam boilers BKZ-210-140F produced by Barnaul boiler plant are installed. The design fuel for boiler №5 of BKZ-210-140F is a milled peat of local deposits, burning together with natural gas or fuel oil.

The varying characteristics of incoming peat (humidity \( W \), ash content \( A \), sulfur content \( S \), combustion heat, degree of contamination, etc.) make adjustments into the combustion process and the overall heat transfer of the boiler [7]. Furthermore, ash fusibility, slagging and ash fouling of heat exchange surfaces in a boiler depend on the qualitative and quantitative chemical composition of the mineral part of the peat and operating temperature [8–10]. Knowledge of the emission characteristics of combustion products (flux densities and emissivity factors) is necessary for pyrometric temperature control and maintenance of optimum operating conditions of the boiler. The choice of a reasonable spectral interval for the pyrometric determination of the combustion products' temperature is possible only if the spectral composition of the radiation is known.

The purpose of this work was a comprehensive experimental and theoretical study of combustion products generated from pulverized peat combustion in the furnace of BKZ-210-140F steam boiler.

2. Characteristics of slag and ash particles obtained during pulverized combustion of peat in the furnace of BKZ-210-140F steam boiler

2.1. Sampling

The paper considers pulverized combustion of milled peat with natural gas in the boiler №5 BKZ-210-140F. In order to determine the chemical composition and dispersity (shapes and sizes) of the particles contained in the combustion products, sampling was carried out in different parts of the boiler system [11]. The names and descriptions of the samples are given in Table 1.

| № of the sample | 1 | 2 | 3 |
|-----------------|---|---|---|
| Name            | Fuel slag | Dry fly ash | Wet fly ash |
| Characteristics of the sample | Dark gray sintered piece | Friable fine powder | Particles in water |
| Place of sampling | Slag bath, located at the bottom of the boiler, under the torch | Under common «collector» | Scrubber |
| Method for removing ash | Mechanical | Precipitation from flue gases | Ash dewatering and transfer |

2.2. Dispersity of particles

To reveal the microstructure of the particles, we used a scanning (focused-beam) electron microscope JSM-6510LV made by JEOL (Japan). Figure 1 shows examples of micrographs of slag and ash particles. The particle sizes vary within wide limits, from tenths of micrometers to 0.4 mm. The shape of the particles varies from irregular to spherical. The irregular (angular) shape of particles with curvilinear surfaces is characteristic of peat slag (sample №1), obtained after the combustion products dip to the bottom of the boiler (a cold funnel). Most of ash particles of dry and wet selection (samples №2 and №3) have spherical shapes and a smooth vitrified texture of the surface. For these systems, histograms of the countable distribution \( \Delta n/(n \cdot \Delta x) \) and particle size distribution functions were obtained, described by the dependence:
where $\mu = \ln(x_n)$ is a natural logarithm of median diameter, $\sigma$ is standard (rms) deviation of the logarithms of diameters from their mean value. More information on the method of statistical data processing carried out can be found in our previous works [11, 12]. The graphical data of the granulometric analysis were expressed in the form of an integral and differential granulometric composition ($P(x)$ and $f(x)$ respectively). The results are shown in Figure 2. Curves $P(x)$ characterize the share distribution of particles in the size classes, which are determined by only one (upper) boundary value, i.e. they determine the proportion of particles smaller than this size.

![Figure 1](image1)

**Figure 1.** Microphotographs of shape and dimensions of slag and ash particles.

![Figure 2](image2)

**Figure 2.** Histograms and particle size distribution functions.
2.3. Chemical composition of particles

To study the chemical composition of peat ash, we used an X-ray fluorescence spectrophotometer EDX-720HS made by «Shimadzu» (Japan). The software of the device allowed not only to reveal the elemental composition, but also to perform the conversion into the oxide form.

Chemical composition for the sample №1: Fe₂O₃ – 43.892 %, SiO₂ – 32.068 %, CaO – 19.058 %, K₂O – 1.447 %, MnO – 1.438 %, TiO₂ – 1.296 %, SrO – 0.550 %, V₂O₃ – 0.251 %.

Chemical composition for the sample №2: Fe₂O₃ – 30.445 %, SiO₂ – 29.227 %, CaO – 20.870 %, Al₂O₃ – 10.485 %, P₂O₅ – 4.478 %, K₂O – 1.359 %, MnO – 1.091 %, TiO₂ – 1.135 %, SrO – 0.277 %, SO₃ – 0.633 %.

Chemical composition for the sample №3: Fe₂O₃ – 39.298 %, SiO₂ – 30.891 %, CaO – 23.525 %, K₂O – 1.516 %, MnO – 1.466 %, TiO₂ – 1.428 %, SrO – 0.364 %, SO₃ – 1.512 %.

From the results of chemical analysis it follows that oxides Fe₂O₃, SiO₂ and CaO predominate in slag and ash, but of different amount and, accordingly, different fusibility. Peat ash is an inert impurity and its composition directly affects the technological processes of using this fuel in heat power engineering. Ash fusibility depend on its qualitative and quantitative composition and determine the formation of ash deposits on the heat exchange surfaces in a boiler. Slagging and fouling deposits depends on ash content of peat and, more importantly, the composition of that ash, and how the ash behaves under the conditions within the boiler.

2.4. Optical properties of particles

Determination of the optical properties (complex refractive index \( n = n_1 - n_2 \cdot i \)) of peat ash particles formed after the combustion of fuel is important for the calculation of heat fluxes and heat exchange.

Goodwin and Mitchner in their works [13, 14] presented the experimental results on the optical properties of coal slags. The proposed semi-empirical rule allows predicting behavior of the refractive index \( n_1 \) in the range 1...8 \( \mu \)m, knowing the weight percentage of each oxide (SiO₂, Al₂O₃, CaO, MgO, TiO₂ and Fe₂O₃) in the mixture. This rule is based on the values of \( n_1 \) for pure oxides with minor modifications, which allow to improve the agreement with the experimentally obtained results. In the range \( \lambda = 8...13 \mu \)m, where 3 absorption bands SiO₂ predominate, the experimental data were approximated by the authors of [13, 14] using the Kramers-Kronig dispersion relations.

Using the analytical relationships presented in [13, 14], in the present work we calculated the optical peat ash constants on the basis of data of the chemical composition of the particles. As the example, Figure 3 shows the dispersion \( n_1 \) and \( n_2 \) for the sample №2.

![Figure 3](image-url)  
**Figure 3.** Optical properties of dry fly ash particles (sample №2), calculated according to the methods [13, 14]: 1 – \( T = 1273 \) K, 2 – \( T = 1573 \) K, 3 – \( T = 1773 \) K.
3. Calculation of the components of the gaseous phase during peat combustion

For the analytical calculation of peat combustion [15], the elementary composition of fuel was used for the working mass (before getting into the mill): \( W^r = 55.1 \% \), \( A^r = 6.6 \% \), \( C^r = 21.7 \% \), \( H^r = 2.3 \% \), \( O^r = 13.2 \% \), \( N^r = 1.0 \% \), \( S^r = 0.1 \% \). Before entering the furnace, the peat is ground, and a dust-air mixture is created, in which the fuel humidity is about 30 \%. The supply of natural gas (NG) is controlled by the boiler attendant. On average, 0.1 m\(^3\) of natural gas is required to burn 1 kg of peat. Table 2 shows the volumetric composition of the components of the gaseous phase under the condition of complete combustion of the fuel at an excess air ratio \( \alpha = 1.25 \). Taking into account the mass fraction of condensate \( z = 0.013 \) in the combustion products, the mass fractions of the gas components were: \( \text{H}_2\text{O} = 0.104 \), \( \text{CO}_2 = 0.181 \), \( \text{SO}_2 = 0.0004 \), \( \text{N}_2 = 0.661 \), \( \text{O}_2 = 0.04 \). Absorption coefficient \( \alpha_{\text{abs}} \) was calculated for the main components of the gaseous phase using the information system Spectra [16]. Figure 4 shows the results of the calculation of combustion gases with pressure \( p = 10^5 \) Pa and temperature \( T = 1273 \) K. The greatest contribution to total \( \alpha_{\text{abs}} \) is made by molecules \( \text{CO}_2 \) (in the range \( \lambda = 4.2 - 4.6 \) \( \mu \text{m} \)) and \( \text{H}_2\text{O} \) (over the entire range \( \lambda = 1 - 13 \) \( \mu \text{m} \)). The role of components \( \text{N}_2 \) and \( \text{O}_2 \) is negligible (the size of \( \alpha_{\text{abs}} \) is about \( 10^6 \) 1/m and smaller).

| Components | Combustion of 1 kg of peat | Combustion of 0.1 m\(^3\) of NG | Peat and NG combustion |
|------------|---------------------------|-------------------------------|-----------------------|
| \( \text{CO}_2 \) | 0.632                     | 0.099                         | 0.731                 |
| \( \text{SO}_2 \) | 0.001                     | -                             | 0.001                 |
| \( \text{H}_2\text{O} \) | 0.825                     | 0.198                         | 1.023                 |
| \( \text{N}_2 \) | 3.253                     | 0.929                         | 4.182                 |
| \( \text{O}_2 \) | 0.172                     | 0.049                         | 0.221                 |
| TOTAL:     | 4.883                     | 1.275                         | 6.158                 |

**Figure 4.** Spectral absorption coefficient of the gaseous phase. (a) spectra of individual components with considering mass fractions, (b) total coefficient in logarithmic (1) and linear (2) scales

4. Mathematical modeling of thermal radiation of combustion products

4.1. Method for modeling of radiation characteristics and emission characteristics

The radiation characteristics of polydisperse systems of spherical particles of a condensed phase were calculated using the Mie theory. To calculate radiation characteristics of individual particles (RCIP) – sections of the attenuation \( \sigma_{\text{att}} \), scattering \( \sigma_{\text{sc}} \) and absorption \( \sigma_{\text{abs}} \) – as the initial data, the dispersion of the complex refractive index \( m \), diffraction parameter \( \rho \) (\( \rho = \pi x/\lambda \)) and particle diameter \( x \) are necessary [17]:
\[ \sigma_{\text{att}} = \pi \tau^2 K_{\text{att}} (m, \rho) / 4, \quad \sigma_{\text{sc}} = \pi \tau^2 K_{\text{sc}} (m, \rho) / 4, \quad \sigma_{\text{abs}} = \sigma_{\text{att}} - \sigma_{\text{sc}}, \tag{2} \]

where \( K_{\text{att}} \) and \( K_{\text{sc}} \) are efficiency factors (dimensionless), defined by the formulas:

\[ K_{\text{att}} = \frac{2}{\rho^2} \sum_{n=1}^{\infty} (2n+1) \text{Re} (a_n + b_n), \quad K_{\text{sc}} = \frac{2}{\rho^2} \sum_{n=1}^{\infty} (2n+1) |a_n|^2 + |b_n|^2 \tag{3} \]

Here \( a_n \) and \( b_n \) are amplitudes of partial waves (Mie coefficients).

Thermal radiation of combustion products is determined by the effects of absorption, scattering, and radiation. They, in turn, are of a statistical nature and are determined by the numerical concentration of particles \( N \).

The amount of condensate particles per unit volume of combustion products is given by:

\[ N = 6 \pi \rho_0 \left[ (1 - z) \rho_\text{z} \pi \int_0^{\infty} x^3 f(x) dx \right]^{-1}. \tag{4} \]

Here \( z \) is the condensate mass fraction, \( \rho_\text{z} \) and \( \rho_\theta \) are the densities of particles and gaseous phase (they depend on temperature \( T \)).

If the medium onto which the radiation beam falls contains a cloud of spherical polydisperse particles of the same composition, then radiation characteristics of a unit volume (RCUV) – coefficients of attenuation \( \kappa_\lambda \), scattering \( \beta_\lambda \) and absorption \( \alpha_\lambda \) – can be calculated by the formula [17, 18]:

\[ \kappa_\lambda = N \int_0^\infty \sigma_{\text{att}} f(x) dx, \quad \beta_\lambda = N \int_0^\infty \sigma_{\text{sc}} f(x) dx, \quad \alpha_\lambda = N \int_0^\infty \sigma_{\text{abs}} f(x) dx. \tag{5} \]

Scattering indicatrix \( \gamma_\lambda = \int_0^\infty \gamma_0(x) f(x) dx \) was presented in a row by Legendre polynomials.

For peat combustion products, as a light-scattering medium, we used integro-differential equation of radiation energy transfer [18]:

\[ (\Omega \nabla) I_\lambda (r, \Omega) + \kappa_\lambda I_\lambda (r, \Omega) = \beta_\lambda \int_{\Omega_0} I_\lambda (r', \Omega') \gamma_\lambda (r', \Omega', \Omega) d\omega' + \alpha_\lambda I_{\text{ABB}, \lambda} (r) \tag{6} \]

Here \( \Omega \) is the direction, \( I_\lambda \) is the spectral intensity of radiation, \( r \) is the coordinate, \( \omega \) is the solid angle, \( I_{\text{ABB}, \lambda} \) is the spectral intensity of absolutely black body radiation (ABB), symbol «'» means the backward scattering.

To solve the integro-differential equation of radiation energy transfer, we used the method of spherical harmonics in \( P_3 \)-approximation for conditions of one-dimensional geometry.

Spectral and integral densities \( (F_\lambda \text{ and } F) \) through the surface unit area perpendicular to the direction of the normal were determined by formulas:

\[ F_\lambda = \int_\Omega I_\lambda (r, \Omega) \kappa d\Omega, \quad F = \int_0^\infty F_\lambda d\lambda. \tag{7} \]

Spectral and integral emissivity factors \( (\varepsilon_\lambda \text{ and } \varepsilon) \) were:

\[ \varepsilon_\lambda = F_\lambda / F_{\text{ABB}, \lambda}, \quad \varepsilon = \int_{\lambda_1}^{\lambda_2} F_\lambda d\lambda. \tag{8} \]
4.2. Initial data for computing experiment

With the help of mathematical modeling, the radiation characteristics and emission characteristics of the combustion products of the peat-gas mixture were studied.

Selected pressure $p = 10^5$ Pa, temperature of the combustion products $T = 1273$ K, $1573$ K, $1773$ K and radiating layer thickness $L = 3...7.5$ m correspond to the most common parameters when burning peat in the boiler №5 BKZ-210-140F at CHPP-4 in Kirov. Using the data on the chemical composition of ash, and the fraction of ash found in the combustion products, we determined the molar mass of the combustion products $\mu = 31.051$ g/mole and the average density of the ash particles $\rho_z = 3.76$ g/cm$^3$.

The selected spectral range $\lambda = 1 – 13$ μm ($\Delta \lambda = 0.005$ μm) corresponds to the maximum fraction of the radiation energy entering in this range.

4.3. Results of calculations of thermal radiation of combustion products

In this section, the results of simulation of thermal radiation were carried out at $f(x)$ with parameters $\mu = 3.391$ and $\sigma = 0.405$ (sample №2). Calculating of RCIP shows that the effective cross sections $\sigma_{\text{em}}$, $\sigma_{\text{sc}}$ and $\sigma_{\text{abs}}$ do not change monotonously (Figure 5). For a given system of particles, the attenuation of transmitted radiation through the medium is mainly determined by scattering, rather than absorption.

The results of RCUV calculations show that the coefficients $\kappa_\lambda$, $\beta_\lambda$ and $\alpha_\lambda$ depend on the wavelength and are proportional to the concentration of particles $N$ (Figure 6). The influence of the gaseous phase (namely CO$_2$) causes a pronounced maximum in the coefficients $\kappa_\lambda$ and $\alpha_\lambda$ in the range $\lambda = 4.2 – 4.6$ μm.

![Figure 5. RCIP of peat ash](image1)

![Figure 6. RCUV of combustion products during combustion of peat-gas mixture](image2)

Figure 7 shows the spectral flux of densities $F_\lambda$ and the corresponding graphs for ABB at different operating temperatures and $L = 7.5$ m. The spectral flux density of the medium is close to the emission of ABB in the absorption bands of the gaseous phase. The integral flux density $F$ increases three-fold with an increase in temperature from 1273 K to 1773 K. Figure 8 gives an example of the dependence of emissivity factor $\varepsilon_\lambda$ on the wavelength at $T = 1273$ K. The graph shows that the radiation has a pronounced selective character. The use of the gray approximation is unacceptable. The integral emissivity factor $\varepsilon$ decreases by 17 % with an increase in temperature from 1273 K to 1773 K.

The results for the conditions of the furnace of a steam boiler indicate that selective radiation from the gaseous phase is superimposed on the continuous radiation of the condensed phase. In the transparency windows of the gaseous phase 1.1, 1.6, 2.1 and 3.5 ... 4.0 μm, it is possible to measure the temperature of the tubes and walls of the furnace, the temperature of ash particles in the flow of the condensed phase of the combustion products. The effect of the emission of the gaseous phase does not affect the radiation receivers of pyrometers with spectral sensitivity in these bands. However, to measure the temperature in transmission bands of gaseous phase, it is necessary to know the emissivity factor of the measured object (tube walls, furnace walls, flux of ash particles, etc.).
In the absorption band \( \text{CO}_2 \) \( 4.2 \ldots 4.6 \ \mu \text{m} \), the emissivity factor \( \varepsilon \) is equal to unity regardless of the level of the temperature of the combustion products, the thickness of the radiating layer (at \( L > 0.4 \ \text{m} \)), the mass fraction of condensate and the optical properties of particles. Measuring the temperature of the combustion products in the \( \text{CO}_2 \) absorption band (\( \varepsilon = 1 \)), assuming that the gas and particle temperatures are equal (\( T_g = T_z \)), and setting this temperature on a pyrometer with a spectral sensitivity of \( 3.5 \ldots 4.0 \ \mu \text{m} \), it is possible to determine the emissivity factor of ash particles of the condensed phase of the combustion products at a given temperature. For this emissivity factor, by solving the inverse problem, one can find the absorption index \( n_2 \) of the complex ash particles at a given temperature and wavelength, which in practical conditions of the furnace is almost impracticable in other ways.

5. Future works and conclusions

The work demonstrates methods and results of the experimental and theoretical study of combustion products for the conditions of pulverized peat combustion in BKZ-210-140F steam boiler. The dispersity, chemical composition and optical properties of slag and ash particles contained in combustion products during the peat combustion are determined. The computational experiment was performed to find the radiation characteristics (coefficients of the attenuation, scattering and absorption) and the emission characteristics of the combustion products (flux densities and emissivity factors) during combustion of peat and gas mixture. Analysis of the results of the emission characteristics allowed us to define spectral regions for measuring the temperature of the combustion products, walls and condensed phase in steam boiler furnace using pyrometric method. In addition, this information makes it possible to determine absorption indices \( n_2 \) of ash particles, which are complex in their chemical composition. The results of the computational experiment for determining the spectral and integral emission characteristics are necessary for the correct assessment of the radiation heat transfer between the combustion products and the reflecting and absorbing wall in the furnace of a boiler, where the proportion of radiation heat transfer reaches 95-97 %.

The work is carried out to further determine the impact of thermal radiation on combustion processes and the efficiency of peat-fired power plants.

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