



Short Communication

Environmentally and economically efficient utilization of coal processing waste



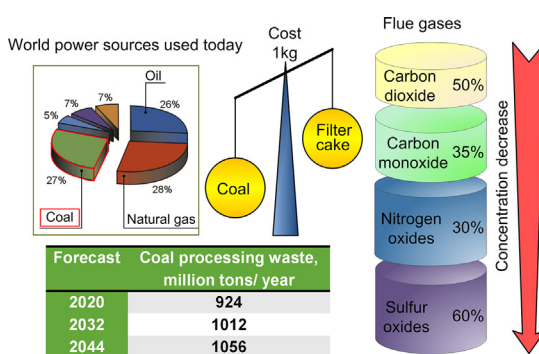
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HIGHLIGHTS

- Filter cakes are the most massive coal processing wastes.
- Areas covered by filter cakes in the world are measured in hundreds of thousands ha.
- Combustion of filter cakes in CWS produces less NO_x and SO_x vs. pulverized coals.
- It is environmentally and economically efficient to burn filter cakes in CWS.
- Low-temperature combustion of CWS provides significant decrease of NO_x, SO_x, CO_x.

GRAPHICAL ABSTRACT



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ABSTRACT

High concentrations of hazardous anthropogenic emissions (sulfur, nitrogen and carbon oxides) from solid fuel combustion in coal burning plants cause environmental problems that have been especially pressing over the last 20–30 years. A promising solution to these problems is a switch from conventional pulverized coal combustion to coal-water slurry fuel. In this paper, we pay special attention to the environmental indicators characterizing the combustion of different coal ranks (gas, flame, coking, low-caking, and nonbaking coals) and coal-water slurry fuels based on the coal processing waste – filter cakes. There have been no consistent data so far on the acceptable intervals for the anthropogenic emissions of sulfur (SO_x), nitrogen (NO_x) and carbon (CO, CO₂) oxides. Using a specialized combustion chamber and gas analyzing system, we have measured the concentrations of typical coal and filter-cake-based CWS combustion products. We have also calculated the typical combustion heat of the fuels under study and measured the ratio between environmental and energy attributes. The research findings show that the use of filter cakes in the form of CWS is even better than coals in terms of environment and economy. Wide utilization of filter cakes solves many environmental problems: the areas of contaminated sites shrink, anthropogenic emissions decrease, and there is no need to develop new coal mines anymore.

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1. Introduction

Up to 45% of all the electric power generated in the world currently falls on thermal power stations (TPS) using traditional energy resources (coal, peat, fuel oil, etc.) (Chen and Xu, 2010). Using coal as fuel

inevitably leads to high concentrations of anthropogenic emissions into the atmosphere adding to global changes in the earth climate (Bowen et al., 2017; Nejat et al., 2015) and provoking the corresponding diseases in the population (Guttikunda and Jawahar, 2014; Nesimi et al., 2013). The list of air pollutants usually includes four key ones responsible for 90% of gross emissions of hazardous substances in various regions of the world (Klimenko and Tereshin, 2010): ash particles, oxides of sulfur (SO_x), nitrogen (NO_x) and carbon (CO_x). In China, for

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Nomenclature

A^d	ash level of dry sample, %
C^{daf}	fraction of carbon in the sample converted to a dry ash-free state, %
H^{daf}	fraction of hydrogen in the sample converted to a dry ash-free state, %
N^{daf}	fraction of nitrogen in the sample converted to a dry ash-free state, %
O^{daf}	fraction of oxygen in the sample converted to a dry ash-free state, %
S_t^{daf}	fraction of sulfur in the sample converted to a dry ash-free state, %
T_g	air temperature, K
V^{daf}	yield of volatiles of coal to a dry ash-free state, %
W^a	humidity, %
Q_s^a	heat of combustion, MJ/kg

example, 70% of all ash particle emissions come from coal energy companies (Chen and Xu, 2010). The situation is similar with other hazardous substances: coal burning power plants are to blame for 90% of all sulfur dioxide (SO₂) emissions, 67% of nitrogen oxides (NO_x), and 70% of carbon dioxide (CO₂) (Chen and Xu, 2010).

Over the last 30 years, many industrialized countries (China, India, USA, Russia and others) have been actively struggling to reduce harmful emissions into the atmosphere by energy providers (Vainikka et al., 2012; Valverde et al., 2016; Meylan et al., 2015; Wei et al., 2015; Fan et al., 2015). Among the current methods, of special interest is the replacement of solid fuel (coal) by coal-water slurry (CWS) and coal-water slurry containing petrochemicals (CWSP) (Jianzhong et al., 2014; Liu et al., 2009a). Such fuels consist of 60–70% of the dry part (coal dust) and 30–40% of the wet part (water, liquid flammable oil products, etc.). Adding water to fuel undoubtedly leads to a decrease in the energy performance of heating plants due to more energy-intensive vaporization. Environmentally speaking, however, a switch from coal to coal-water slurry fuel helps to significantly reduce the anthropogenic emissions of sulfur and nitrogen oxides (Wang et al., 2010; Jiang et al., 2007; Sharabura et al., 2012; Yang et al., 2016).

It is of great current interest to study the impact of combustion temperature and component concentrations of coal fuels on the concentrations of anthropogenic emissions. Another subject of interest is the feasibility of using coal processing waste rather than coal itself as a component of CWS. A comparative analysis of the recent publications (Kijo-Kleczkowska, 2016; Jiang et al., 2007; Sharabura et al., 2012; Baranova et al., 2009; Parres-Esclapez et al., 2010; Glushkov et al., 2016b) has shown that the most widespread coal processing wastes are filter cakes. These wastes are the result of coal washing when coal slurry thickens with the help of surfactants (floculants). The slurry with high solids concentration is then filtered and excess moisture is removed in the process. A moist high-ash remainder is called a cake. The share of the dry part in the cakes range from 39% to 57% (see Table 1). Solid particles in filter cakes are 100 μm in size. Wet cakes per se are ready-made CWS (since the coal concentration in CWS is usually between 40% and 60%).

The purpose of this work is to compare the environmental and energy indicators describing the low-temperature combustion of coal and coal-water slurry made of the most widespread coal processing wastes – filter cakes.

2. Experimental setup

The scheme of the experimental setup used in this research is shown in Fig. 1. We used coal of five ranks as fuel as well as five types of CWS

Table 1

Results obtained from proximate analysis of coal and filter cakes.

Sample	W ^a , %	A ^d , %	V ^{daf} , %	Q _s ^a , MJ/kg
Gas coal	0.76	17.8	41.36	27.82
Flame coal	5.17	13.9	41.59	25.79
Bituminous coal	2.05	14.65	27.03	29.76
Nonbaking coal	2.89	18.07	15.07	27.65
Low-caking coal	2.76	21.68	27.40	26.23
Filter cake of gas coal (dry)	–	33.82	43.11	22.16
Filter cake of flame coal (dry)	–	36.99	41.47	19.24
Filter cake of bituminous coal (dry)	–	26.46	23.08	24.83
Filter cake of nonbaking coal (dry)	–	21.20	16.09	26.92
Filter cake of low-caking coal (dry)	–	50.89	30.16	15.23

based on the corresponding filter cakes. Results obtained from the proximate analysis of the fuel samples under study are presented in Table 1. Table 2 provides the results of the ultimate analysis. For the water ratio of filter cakes, see Table 3, which clearly shows that filter cakes are indeed coal-water slurry fuel ready for combustion.

Stainless-steel mesh brazier 2 (mesh size 0.5 × 0.5 mm) where fuel 3 is deposited passed into combustion chamber 1 (0.3 m wide, 0.28 m high, and 0.25 m deep) through a cylindrical hole (0.1 m in diameter). Before each experiment, the fuel batch was weighed on ViBRA HT 84RCE analytical balance 4. The mass of the batch was 15 g in each experiment.

Hot-air flow in combustion chamber 1 was formed by compressor 5 (power 0.25 kW, flow rate no more than 1200 l/min) and air heater 6 (power 11 kW, maximum outlet gas temperature 1100 °C). The velocity (V_g) of the oxidation flow at the inlet of the combustion chamber was maintained at the level of 2 m/s. The oxidizer temperature (T_g) varied in the range of 500 to 1100 °C. We measured the oxidizer flow velocity by optical methods similar to those described in (Glushkov et al., 2016a).

The combustion chamber had two access holes 0.02 m in diameter located in the side walls. Thermocouple 7 (type K, temperature range 0–1100 °C, error ± 3 °C, response rate no more than 1 s) was placed into the first orifice. A signal came from thermocouple 7 to recorder 8 and controlled the air temperature in the corresponding section of chamber 1. The second hole was meant for modular probe 9 of gas analyzer 10. Modular probe 9 collected samples of flue gases during fuel combustion in the chamber and was connected to the socket of gas analyzer 10. A collected sample passed into the case of gas analyzer 10 through connecting cable 11 with sensors measuring the concentration of components in a gas-air mixture: O₂, H₂, CO₂, CO, SO₂, and NO_x. See Table 4 for the specifications of the gas analyzer for each of the listed components.

Gas analyzer 10 was connected by a USB cable to PC 12 with specialized EasyEmission software installed. It displays the measured values on the screen as tables and characteristic curves. The analyzer takes data from probe 9 every five seconds to select a sample.

A combustion mode (fuel type) was selected from the analyzer menu for each type of fuel. For the selected mode, the gas analyzer presets include specific coefficients to be used in formulas for calculating the parameters in question (to ensure the accuracies from Table 4). Table 5 shows the types of fuels used in the experiments and their corresponding modes. We used the “Coal gas” preset of the gas analyzer. Such the choice is because software developers recommend to use this particular preset for the comparative analysis for concentrations of anthropogenic emissions during combustion of bituminous coals and their processing wastes with different properties. Using the “Coal gas” preset, the gas analyzer estimates concentrations of the main components of any coal.

3. Results and discussion

Figs. 2–4 show the results obtained from the comparison of concentrations of the most hazardous anthropogenic emissions (CO, CO₂, NO_x,

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