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Major gas emissions from combustion of slurry fuels based on coal, coal waste, and coal derivatives

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ABSTRACT

This research experimentally determines the major gas emissions from the industrial combustion of coal, coal processing waste, and coal derivatives in the form of traditional coal dust as well as slurry fuels with water and flammable additives. Several types of coal are considered: gas coal, flame coal, bituminous, non-coking and low-caking coal, as well as coal processing waste (filter cakes), coal derivatives (coke, semi-coke), and flammable liquids (industrial oil waste, fuel oil). Experimental data for charcoal and carbon dust from recycled car tires are presented as well. The concentration is evaluated for the most hazardous gas emissions: sulfur and nitrogen oxides. A number of factors defining the said concentrations are established: the quality of components, their elemental composition and concentration (40–60% coal, 30–50% water, 5–15% flammable liquid); slurry preparation method (homogenizer or cavitator); coal grind (8–250 μm); and the mass of the batch (0.5–1.5 g). In particular, changing coal concentration in a slurry from 40 to 60% increases the emission of nitrogen oxide by 35% and sulfur oxide by 67%. Varying water concentration from 30 to 50% decreases the emission of nitrogen oxide by 17% and sulfur oxide by 62%. Increasing the flammable liquid concentration from 5 to 15% slightly lowers the emission of nitrogen oxide (by 5%), while the sulfur oxide emission grows by 28%. The advantages of coal-water slurry containing petrochemicals combustion are identified over coal. Moreover, the main limitations are determined for large-scale usage of slurry fuels instead of traditional heat and power industry fuels.

1. Introduction

Coal is an integral part of the global energy balance along with the other two main natural resources – oil and natural gas (Rodriguez-Iruretagoiena et al., 2016; Saikia et al., 2016; Sehn et al., 2016; Dalmora et al., 2016; Ramos et al., 2017; Fdez-Ortiz de Vallejuelo et al., 2017; Wilcox et al., 2015). For the last decade, coal consumption rate has been rapidly increasing worldwide, approaching the oil consumption rate (Liu et al., 2017; Li et al., 2016; Su et al., 2017). The global energy connectivity trend, covering most of the countries, leads to an increase in electrical power generation (Agudelo-Castañeda et al., 2017; Schneider et al., 2016; Sanchís et al., 2015; Tezza et al., 2015; Sindelar et al., 2015). To meet the global energy demand, today more than 39% of electric power is generated by coal fuel combustion. According to Su et al. (2017) and BP Statistical Review of World Energy 2016 (2016), this number will drop down to 33% by 2035. However, since global electric power consumption will grow 43% over the same period, it only demonstrates the stability of coal-fired power industry and its development prospects (Su et al., 2017).

For the past several years, coal extraction has shown a sustained growth in APAC countries: China, India, Indonesia, Australia, and Russia. Southeast-Asian countries continue to increase the production capacity, demanding more energy sources. Since there are not so many oil deposits in Asian and Pacific countries, coal becomes the main energy source in the region (Li et al., 2016; Su et al., 2017; BP Statistical Review of World Energy, 2016, 2016). Table 1 represents global coal consumption dynamics as well as coal consumption in certain countries.

The environmental effect of coal as the main solid fuel appears at every production step (Wang et al., 2016; Aijun et al., 2017; Li et al., 2008), from extraction to transportation to power generation and transfer. Coal extraction means landscape disturbance, creation of mines, quarries, and disposal areas; coal transportation entails transit losses as well as solid particles dispersion into soil

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Nomenclature

CWS	coal-water slurries
CWSP	coal-water slurries containing petrochemicals
A^d	ash level of dry sample, %
C^{daf}	fraction of carbon in the sample converted to a dry ash-free state, %
C_i	cost of components, $
D_i^{NOx}	relative parameters describing the heat of coal, CWS or CWSP combustion with regard to the cost of components and concentration of emissions NO_x, MJ/$·ppm
D_i^{SOx}	relative parameters describing the heat of coal, CWS or CWSP combustion with regard to the cost of components and concentration of emissions SO_x, MJ/$·ppm
$D_i^{NOx\&SOx}$	relative parameters describing the heat of coal, CWS or CWSP combustion with regard to the cost of components and concentration of emissions NO_x and SO_x, MJ/$·ppm
H^{daf}	fraction of hydrogen in the sample converted to a dry ash-free state, %
m	fuel mass, g
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^{daf}	fraction of sulfur in the sample converted to a dry ash-free state, %
T_g	air temperature, K
T_f,	flash point, K
T_{ign},	temperature of ignition, K
Q^a_s,	heat of combustion, MJ/kg
V^{daf}	yield of volatiles of coal to a dry ash-free state
W^a	moisture, %
ρ	density, kg/m^3
φ_c	coal content, %
φ_o	oil content, %
φ_w	water content, %

and atmosphere. Fuel combustion, while being the main energy generating method, is also the greatest source of environmental pollution (Dias et al., 2014; Cutruneo et al., 2014; Oliveira et al., 2014; Martinello et al., 2014; Arenas-Lago et al., 2014; Osório et al., 2014; Garcia et al., 2014; Pérez et al., 2014). Carbon fuel combustion releases the following substances into the atmosphere: fly ash, unburnt fuel particles, sulfur dioxide and trioxide, nitrogen oxides, and fluoride compounds (Wang et al., 2016; Aijun et al., 2017; Li et al., 2008; Agudelo-Castañeda et al., 2017). Over 50% of global SO_x emissions, generated by power industry, are from coal combustion (International Energy Agency, 2011). In the case of NO_x emissions, coal combustion contributes approximately 20% (International Energy Agency, 2011). Tables 2 and 3 contain predicted data (International Energy Agency, 2011) of anthropogenic emissions caused by different fuel types.

Along with the anthropogenic emissions (Hampf and Rodseth, 2015), coal processing generates a large amount of high-ash waste (filter cakes), whose overall mass today is estimated as tens of millions of tons (International Energy Outlook with projections to 2040, 2013). Annual increase in this type of waste is directly dependent on coal extraction growth. The combustion of coal processing waste as a component of fuel slurries is becoming a highly important way of its industry-scale recycling. Flammable coal waste is the most promising component for the preparation of coal water slurry (CWS) and coal water slurry containing petrochemicals (CWSP) (Glushkov et al., 2016b, 2016c; Liu et al., 2009b).

Several authors (Glushkov et al., 2016b, 2016c; Liu et al., 2009b) established, that coal-water slurry fuel implementation leads to increased coal combustion efficiency, provides coal waste recycling, and lowers hazardous atmospheric emissions (nitrogen and sulfur oxides in particular) (Dmitrienko et al., 2017). CWS combustion is considered a virtually non-waste technology. Small particles of no more than 50 μm as a component of slurry fuel either burn out completely or do not burn at all (e.g., metal oxides). Using coal waste in CWS composition significantly simplifies the technology for fuel preparation, eliminating the expenses for primary grinding, and lowers environmental fines for coal processing waste (Khodakov, 2007; He et al., 2015).

Table 1
Coal: Consumption[a], Million tons oil equivalent (BP Statistical Review of World Energy, 2016, 2016).

	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
US	574.5	565.7	573.3	564.2	496.2	525.0	495.4	437.9	454.6	453.8	396.3
Canada	31	30.1	31.2	30.3	24.2	25.2	22.2	21.2	20.8	21.4	19.8
Brazil	13	12.8	13.6	13.8	11.1	14.5	15.4	15.3	16.5	17.6	17.4
Denmark	3.7	5.6	4.7	4.1	4	3.8	3.2	2.5	3.2	2.6	1.8
France	13.4	12.4	12.8	12.1	10.8	11.5	9.8	11.1	11.8	8.7	8.7
Germany	81.3	84.5	86.7	80.1	71.7	77.1	78.3	80.5	82.8	78.8	78.3
Italy	16.5	16.7	16.3	15.8	12.4	13.7	15.4	15.7	13.5	13.1	12.4
Kazakhstan	26.9	28.3	31.1	33.8	30.9	33.4	36.3	36.5	36.3	35.5	32.6
Poland	55.1	57.4	55.9	55.2	51.8	55.1	55	51.2	53.4	49.4	49.8
Russia	94.6	97	93.9	100.7	92.2	90.5	94.0	98.4	90.5	87.6	88.7
Spain	20.5	17.9	20	13.5	9.4	6.9	12.8	15.5	11.4	11.6	14.4
UK	37.4	40.9	38.4	35.6	29.8	30.9	31.4	39.0	37.1	29.9	23.4
South Africa	80.1	81.5	83.6	93.3	93.8	92.8	90.4	88.3	88.9	90.1	85.0
China	1318.2	1448.4	1576.9	1603.1	1680.4	1743.4	1899.0	1923.0	1964.4	1949.3	1920.4
India	211.3	219.4	240.1	259.4	282.8	292.9	300.4	330.0	355.6	388.7	407.2
South Korea	54.8	54.8	59.7	66.1	68.6	75.9	83.6	81.0	81.9	84.6	84.5
Taiwan	35.3	37	38.8	37.0	35.2	37.6	38.9	38	38.6	39	37.8

[a] Commercial solid fuels only, i.e. bituminous coal, anthracite (hard coal), lignite and brown (sub-bituminous) coal, and other commercial solid fuels. Excludes coal converted to liquid or gaseous fuels, but includes coal consumed in transformation processes.