



Environmental, economic and energetic benefits of using coal and oil processing waste instead of coal to produce the same amount of energy

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ABSTRACT

The replacement of coals by less environmentally hazardous coal-water slurries with and without petrochemicals is often discussed with an emphasis on quite a long list of advantages of composite fuels. In this research, we perform a compound analysis of the main prospects of switching from coal to slurries containing coal and oil processing waste. The main focus is on comparing a group of parameters to produce the same amount of heat from the combustion of coals and high-potential fuels. The compound analysis includes fuel consumption, the most hazardous anthropogenic emissions (sulfur and nitrogen oxides), the mass of the ash residue, the cost of components as well as their properties and concentrations. The numerical values of the relative efficiency factor of fuels based on municipal and industrial wastes vary in a wide range from 2 to 165. The best results are shown by the slurries based on flotation wastes (filter cakes) of coking and nonbaking coals (ranks C and N). For them, the aggregated criterion indicators are 70–90% higher than for the respective coals. A forecast has been made on the amount of energy that can be generated using fuels from wastes. According to our forecast, the waste-based fuels under study may be used to generate 773 TWh of energy annually.

1. Introduction

The root of many economic, social, inter-ethnic, political, geopolitical and environmental crises is in the distribution of energy resources and different stands on this problem. Over the last decades, an opinion has formed that energy resources rule the world [1]. Three main challenges now dominate the discussion about the development paradigm of the world community. *First*, the resources for the preparation of traditional energy fuels are being depleted quite rapidly, and their range is limited [2]. *Second*, the prices of energy resources have been especially unsteady lately. Lingering economic and geopolitical crises are stifling many regions and states [1–3]. *Third*, the combustion of even high-quality energy resources with limited reserves cause significant environmental problems, for instance, the anthropogenic emissions of sulfur and nitrogen oxides as well as greenhouse gases [4]. These issues primarily apply to oil and gas. Consequently, coal consumption in the world is growing rapidly, approaching oil consumption levels or even exceeding them in some states.

Nowadays, the combustion of coal-based fuels generates almost 39% of the total electric energy produced in the world. By 2035, electric energy consumption will have grown by 40–45%, so coal-fired power industry has its future secured. World energy production relies

heavily on coal-fired thermal power stations and boiler plants [5–10]. New coal-burning power stations and boiler plants appear every year, despite severe environmental implications. As the energy demand increases, coal-fired thermal power stations and boiler plants will only reinforce their leading positions in the coming decades. A 40–42% growth is expected by 2020 [8,11]. At the same time, many Europeans highly object to the operation of old nuclear power plants and to the construction of new ones. As a result, even the governments of such developed countries as Germany, Italy, and Great Britain have to revise their strategies of energy development. For instance, the nuclear strategy of the German government has changed 3–4 times over the last 15 years.

According to RF Presidential Decree No 5 as of January 5, 2016, the year of 2017 was declared the year of environment in Russia. Many states of Europe, Asia, and North America focus their full attention on environmental aspects and global warming. The greatest proportion of emissions comes from the energy sector relying on fossil fuels. Being the main solid fuel, coal exerts a significant negative impact on the environment at all the stages of power generation [5,9,12–15]. Coal extraction involves landscape change as well as the formation of mines, quarries and disposal areas. Coal transportation leads to losses through the dispersion of solid particles into the ground and atmosphere.

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Nomenclature

| | |
|----------------------|--|
| CLF | composite liquid fuels |
| CWS | coal-water slurries |
| CWSP | coal-water slurries containing petrochemicals |
| A^d | ash level of dry sample, % |
| $A_{relative}$ | relative compound parameter |
| $C_{SOx}^{absolute}$ | absolute value of sulfur oxides emissions from fuel volume combustion, ppm-τ |
| $C_{NOx}^{absolute}$ | absolute value of nitrogen oxides emissions from fuel volume combustion, ppm-τ |
| $C_{SOx}^{relative}$ | relative value of sulfur oxides emissions from fuel volume combustion |
| $C_{NOx}^{relative}$ | relative value of nitrogen oxides emissions from fuel volume combustion |
| $M^{absolute}$ | absolute value of typical fuel masses, kg |
| $M^{relative}$ | relative value of typical fuel masses |
| $M_{absolute}^{ash}$ | absolute value of ash masses, kg |

| | |
|----------------------|--|
| $M_{relative}^{ash}$ | relative value of ash masses |
| $NO_x^{absolute}$ | absolute concentrations of nitrogen oxides emissions from fuel combustion, ppm |
| $NO_x^{relative}$ | relative concentrations of nitrogen oxides emissions from fuel combustion |
| $S_{absolute}$ | absolute value of fuel cost, \$/kg |
| $S_{relative}$ | relative value of fuel cost |
| $SO_x^{absolute}$ | absolute concentrations of sulfur oxides emissions from fuel combustion, ppm |
| $SO_x^{relative}$ | relative concentrations of sulfur oxides emissions from fuel combustion |
| T_f | flash-point temperature of liquid combustible component, K |
| T_g | air temperature, K |
| T_{ign} | ignition temperature of liquid combustible component, K |
| $Q_{s,v}^a$ | low heating value, MJ/kg |
| V^{daf} | yield of volatiles of coal to a dry ash-free state |
| W^a | moisture, % |

Carbon fuel combustion produces fly ash, sulfur and sulfuric anhydrides, nitrogen and sulfur oxides, as well as fluoride compounds. Over 50% of the world's SO_2 emissions generated in the energy sector come from coal combustion. When it comes to NO_x emissions, the contribution of coal combustion makes up 20%. Countries with advanced coal-based heat and power industries are the ones adding the most to the problem of global warming. Coal-fired power plants have a well-known negative impact on the humankind and environment such as illnesses, deaths, human migration, extinction and migration of animals, and reduction of eco-friendly woodlands.

Coal processing produces a lot of high-ash wastes known as filter cakes in Russia. The mass of these wastes totals tens of millions of tons [16]. The annual increment of such wastes is directly proportional to the growth of coal mining [1–3]. Large-scale recovery of rock fines, sludge, and coal processing wastes by burning them as part of fuel slurries is becoming increasingly relevant. Moreover, low-rank coals, which are extracted in large volumes, also need to be utilized effectively [17,18]. Combustible coal processing wastes are the most promising components for coal-water slurries with and without petrochemicals (CWS and CWSP) [3]. Using coal-water fuel improves the effectiveness of coal combustion, provides a way to recycle coal sludge and reduces harmful emissions into the atmosphere including nitrogen and sulfur oxides [16–21]. Using coal processing wastes as a basis for coal-water slurries eliminates the costs for fuel treatment (grinding) and reduces the penalties for environmental pollution with coal processing wastes. However, filter cakes have fewer carbon and volatile components than coals. These indicators of cakes are comparable to those of low-rank coals. As a result, filter cakes serve as low-reactive fuel components, making the ignition delay time of such fuels much longer [16]. For most filter cake types, the ignition lag is several times greater than that of coals. Similar conclusions can be made from the analysis of oil sludge heating and ignition patterns. One of the ways to accelerate the CWS and CWSP fuel ignition is adding flammable liquids, such as waste turbine, transformer, compressor, and engine oils as well as oil sludge [16]. Another promising approach consists in increasing the concentrations of highly reactive solid fuel components in CWS and CWSP fuels.

Recent studies have determined the integral characteristics of the ignition and combustion of the most promising CWS and CWSP fuels based on various components, from low-rank coals to coal and oil processing wastes [16,19–22]. However, there is still a question about the typical differences in the consumption of coal and CWS/CWSP fuels generating the same amount of energy. Coal-water slurries are inferior to high-carbon fuels in the proportion of carbon. Their erratic ductility

makes it necessary to use chemical additives and stifles their advancement. The choice of CWS and CWSP component composition is challenging due to a large number of varying parameters. At a first approximation, we can use the methods from previous studies [19–21] to explore these issues. The most rational choice seems to be a compound analysis of energy and economic indicators of switching from coal to CWS and CWSP fuels, taking into account anthropogenic emissions, ash residue, as well as fire and explosion safety. It is sensible to perform such an analysis for fuel compositions that differ greatly in cost, heating value, and environmental performance. This will facilitate the objective assessment and development of the current perceptions from [4,18,22–31] about the positive environmental future of coal-fired power industry if slurry fuels are used.

Using composite fuels from coal processing wastes (filter cakes, sludge and their mixtures) has a great social, economic and international importance. *First*, it can help eliminate the huge amounts of the accumulated wastes. In many countries, industrial enterprises fail to implement the recycling of their wastes in practice. England, Norway and Italy alone bury 60–80% of waste in landfills. The United States, responsible for more than 30% of global waste (240 million tons), dump more than a half of it below the ground [32]. The situation is similar in Russia, China, India and other countries [32–34]. *Second*, involving waste in heat and power generation sector will expand the scope of energy industry raw materials in many regions of the world, save solid and liquid hydrocarbons and reduce the environmental load. *Third*, it will increase the fire and explosion safety of coal-burning energy providers, since flammable and fire-hazardous fuels (coal dust, gas or fuel oil) will be replaced by wet flotation waste, coal sludge and other types of waste as part of composite fuels with higher combustion temperatures. *Fourth*, adding water to wastes makes it possible to significantly reduce the anthropogenic emission concentrations. A fraction of the coal component is replaced by environmentally neutral water. Besides, water decreases the combustion temperature, which has a direct impact on the formation of hazardous gases released in the combustion. *Fifth*, when filter cakes and CWS/CWSP fuels are used, the temperature in the combustion chamber is lower than in case of burning coal dust, since slurries contain water (its evaporation consumes energy). As a result, the temperature in the combustion chamber changes smoothly and steadily. There are no temperature jumps, which also leads to a longer fleet life of thermally loaded equipment.

Thus, it becomes obvious that the prospects of waste-based slurry fuel technology can make the environmental and energy situation in the world more favorable. To confirm the above, it is necessary to carry out qualitative and quantitative evaluation of various aspects of using

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