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Research article

Differences in ignition and combustion characteristics of waste-derived oil-water emulsions and coal-water slurries containing petrochemicals

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A R T I C L E I N F O

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A B S T R A C T

The creation of general-purpose combustion chambers and drafting of regulations (unified technologies) which would secure efficient combustion of complex fuel compositions necessitates reliable experimental data concerning the main ignition and combustion characteristics of high-potential oil-water emulsions, coal-water slurries and coal-water slurries containing petrochemicals. In the conducted experiments, we varied the main factors of heating, ignition and combustion processes: properties and concentrations of solid and liquid fuels, the temperature in the model combustion chamber, and initial sizes of fuel droplets. It was established that ignition delay times of oil-water emulsions and coal-water slurries containing petrochemicals based on typical industrial waste can differ 3–4 times. The combustion heat of typical waste industrial oil (collected from power plants after use) makes up 50–90% of the total combustion heat of oil-water emulsions and coal-water slurries containing petrochemicals. The main anthropogenic emission concentrations (sulfur and nitrogen oxides) are 5–6 times higher from burning oil-water emulsions than from burning coal-water slurries containing petrochemicals. We have defined thermal conditions providing close values of the main combustion parameters for oil-water emulsions and fuel slurries. Using two approaches, we have calculated relative efficiency indicators (criteria) of burning high-potential oil-water emulsions, coal-water slurries, and coal-water slurries containing petrochemicals versus coal. These criteria take into account environmental, economic and energy performance. Environmental and energy performance indicators of coal-water slurries containing petrochemicals are 35–90 times higher than those of oil-water emulsions, and 6–16 times higher than those of coal dust fuel.

1. Introduction

Some countries (the USA, China, Russia and Saudi Arabia) derive a large share of their budget revenue from selling energy resources (coal, oil and gas). This revenue can constitute as much as 70–80% of their annual budget. These conditions make it profitable for exporting countries to raise the cost of energy resources. In a highly competitive market, though, it is quite risky and irrational to increase the cost without a reasonable basis. Therefore, many of the exporting countries justify such an increase by an improved quality of energy resources, and tend to perform numerous stage procedures aimed at the beneficiation of the extracted fossil fuels. Coal and oil processing is accompanied by the production of large volumes of waste (namely, oil sludge and coal processing waste) [1–3]. Russia alone yearly accounts for several million tons of such waste production [4]. The trends in the extraction and processing of coal of different ranks (lignite, bituminous coals and anthracites) all over the world [1–3] allow us to forecast a nonlinear growth in volumes of the corresponding wastes over the time.

The modern recovery methods for coal and oil processing wastes are classified in the following way: combustion in power plant furnaces (at thermal power stations and boiler plants); using solid waste with a high carbon content to protect slopes from erosion and build sound barriers along highways, as well as in hydraulic construction and in the construction of breeding grounds; adding oil sludge and used fuel and lubricants to ceramic batches (in brick making) or in the production of expanded clay and small-sized building products; burial of industrial wastewater in the Earth's deep interior; and storage at special sites. It is a highly promising, yet an understudied approach to involve all wastes in the process cycles of gasification to produce syngas with the required component composition and characteristics [5–9].

For economic reasons, it is most rational [4] to recover industrial waste by burning it in combustion chambers of power plants. However, the energy and environmental performance indicators of such processes are not high [4]. In particular, numerous oil-water emulsions and

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Nomenclature

Abbreviations

CWS coal-water slurry
CWSP coal-water slurry containing petrochemicals
OWE oil-water emulsion
UTO used turbine oil

Symbols

A^d Ash, %
A_i^{CO2}, A_i^{NOx}, A_i^{SOx} Relative parameters of CO_2, NO_x, and SO_x emissions (*i* describes used turbine oil, oil-water emulsion and coal-water slurry containing petrochemicals)
B_i Dimensionless indicator for environmental, economic and energy performance factors of fuel combustion (*i* describes used turbine oil, oil-water emulsion and coal-water slurry containing petrochemicals)
C_i Specific cost of fuel component, \$/kg
D_i Relative parameters describing g the heat of fuel combustion with regard to the cost of components and concentration of emissions (*i* describes used turbine oil, oil-water emulsion and coal-water slurry containing petrochemicals)
C^{daf}, H^{daf}, N^{daf}, O^{daf} Fraction of carbon, hydrogen, nitrogen, and oxygen in filter cakes converted to a dry ash-free state, %
M_i Relative energy parameters of used turbine oil, oil-water emulsion and coal-water slurry containing petrochemicals combustion vs. coal (with regard to economic, environmental and energy performance indicators)
P_i Relative indicator describing the cost of coal vs. the cost of fuel (*i* describes used turbine oil, oil-water emulsion and coal-water slurry containing petrochemicals)
Q_s^a Heat of combustion, MJ/kg
R_d Initial radius of droplet, mm
S_t^d Fraction of sulfur in the sample converted to a dry state, %
T_d Temperature in the center of slurry droplet, °C
T_g Temperature in the combustion chamber, °C
T_g^{min} Minimum oxidizer temperature required for stable ignition of CWSP, °C
V^{daf} Yield of volatiles in filter cakes converted to a dry ash-free state, %

Greek symbols

τ Time, s
τ_b Combustion time, s
τ_d Ignition delay time, s

slurries based on coal and oil processing wastes are not actively used at heat and power industry enterprises. This is primarily explained by the fact that technologies and conditions of their efficient combustion have not yet been fully elaborated. To develop technologies for efficient combustion of OWE and coal-water slurries containing petrochemicals, it is sensible to study the main modes of their ignition and combustion with the most typical properties and concentrations of combustible components, and to define the main characteristics of ignition and combustion processes.

The analysis of the review Refs [4, 10] allows us to conclude that the following characteristics are most relevant for the complex evaluation of the potential of such fuels: ignition delay times; combustion (burnout) time of composition particles and droplets; minimum threshold ignition temperature; maximum combustion temperature; environmental indicators of combustion (carbon, sulfur and nitrogen oxide concentration); ash content; and heat of combustion. In order to identify efficient thermal conditions of OWE and CWSP combustion, it is necessary to vary the main factors of the processes under study: properties and concentrations of solid and liquid fuel components, model combustion chamber temperature and initial fuel droplet sizes. The range of raw materials for producing OWE and CWSP is extremely wide. By analyzing the research findings [4, 10], we can make a conclusion that the following can serve as OWE and CWSP components: oil-water emulsions, oil sludge, used industrial and engine oil, heavy coal-tar products, resins, filter cakes, ground rock, car tire recycling products, etc.

Studies [11–15] present the results of theoretical and experimental research into ignition and combustion processes of OWE. We have determined promising components and their concentration in OWE composition to improve rheological, environmental, economic and energy performance indicators of their combustion. We have also established the scale of impact of oil on the delay of heating, evaporation, ignition and combustion of OWE compositions. We have studied the effects of boiling, dispersion and explosive combustion of OWE. The concepts of OWE ignition mechanisms have been expanded. We have established high-potential additives to OWE, enabling to reduce the negative factors of OWE combustion.

Studies [16–20] present the results of theoretical and experimental research into ignition and combustion processes of CWS and CWSP fuels based on industrial waste. The main problems of studying these processes have been emphasized. We have analyzed the decisive effects and factors (component concentration, particle sizes of a solid combustible component of a fuel slurry, oxidizer temperature, properties of components, method and time of slurry preparation, and others), which influence the ignition delay and sustainability of slurries based on coal and oil processing wastes (coals of different ranks, filter cakes, used motor, transformer and turbine oils, OWE, etc.). We have specified promising avenues for modern concepts of CWS and CWSP ignition and combustion. The reasons have been identified limiting the active application of coal-water fuel compositions in heat and power industry. The priority of using CWSP is mainly conditioned by an extremely wide range of raw materials, lower energy consumption for their preparation and combustion, as well as considerable variations in sustainable combustion parameters of fuel slurries.

The main problem with applying the fuel compositions under study consists in the absence of comparative analysis results for integral characteristics of OWE and CWSP combustion processes [4]. It is crucial to determine the optimal component concentration and thermal preparation conditions allowing for efficient combustion of OWE and CWSP. By solving this problem, we can create unified technologies and general-purpose combustion chambers, preparation and fuel injection systems, as well as draft regulations of efficient combined recovery of numerous coal and oil processing wastes. It is reasonable to conduct a complex analysis of OWE and CWSP applicability in heat and power industry using algorithms and research procedures from previous studies [21–23].

The purpose of this work is to analyze experimentally the integral characteristics of the ignition and combustion of OWE and CWSP based on coal and oil processing wastes. It is important to establish the possibility of changing not only the ignition and combustion characteristics but also regimes and dominant mechanisms by changing the composition of waste-derived fuel slurries and emulsions.