Combustion of the waste-derived fuel compositions metallized by aluminium powder

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ABSTRACT

Usage of the waste-derived fuels is a very promising way for different industrial processes. It can yield both environmental and economic benefits, but for the heat production to be effective, fuel compositions must be prepared in an intelligent way. The combustion heat of such fuels is lower than that of conventional ones, so their improvement and successful application is in our best interests. Our goal was to investigate experimentally the effect of adding a small amount of aluminium powder (particle size $\sim$ 10 µm) to optimize waste-derived coal-water slurry with waste petrochemicals. We show the optimal metal concentration rate (3 wt%) that provides a significant increase in the maximum combustion temperature (by more than 100°), while keeping the ignition delay time at the appropriate level. Moreover, another mode is possible, when the combustion temperature is almost independent of the temperature inside the combustion chamber. The combustion duration and underburning levels were observed, too.

1. Introduction

The development of industry in the world is conjugated with ever-growing energy consumption. Local decreases in this trend result from different economic crises but global energy consumption rate is growing. It achieved 13 billion tons of oil equivalent in 2014 (as we can see from [1]). To avoid the evident final on this way, industrial countries start using different measures to switch their industry to energy efficient production. One of the most popular solutions is the usage of various wastes and biomass as new type of components for industrial fuels [2,3]. The attraction of this way is based on two economic and ecological factors: it produces relatively cheap and readily available fuels and allows the utilization of a huge amount of already accumulated wastes. In addition, the current production of these wastes provides a quasi-infinite resource base for technological cycles based on the proposed waste-derived fuels.

The usage of wastes determines lower heating efficiency of the proposed fuels as compared to traditional types. However, low-grade coals, wastes of coal- and oil-processing and waste oil products can be promising components of efficient fuel compositions. Mixing different wastes is the most intelligent way to produce effective and environmentally friendly fuels with pre-defined properties. The investigations of properties of different combustible wastes give a good background for this [4].

The waste-derived coal-water slurries doped by waste petrochemicals (CWSP) are the subject of numerous recent papers (for example [5–7]). They attract a lot of attention of the scientific community because the properties of these fuels allow their usage in the widespread industrial heating systems without principal modifications. The presence of large amounts of water leads to much lower combustion temperatures and, as a result, much lower emissions of sulfur dioxide and oxides of nitrogen [5]. In addition, the production of greenhouse gases is essentially decreased as compared to conventional coals due to the presence of a large amount of hydrogen ions in the mixture of steam and combustible volatiles as described in [8]. The CWSP compositions provide higher calorific value than pure coal–water slurries due to the presence of up to 15% of oil-based components with relatively high combustion heat. Furthermore, they have much lower ignition temperature and significantly shorter ignition delay time due to more rapid production of combustible volatiles [4,5]. All these features make the CWSP very suitable for industrial heaters. However, to reduce fuel consumption, the combustion heat needs to reach the maximum possible values for compositions with these components [5]. On the other hand, the stability of combustion can also be improved by the optimal choice of additional fuel components [4].

The unique feature of slurry fuels is the possibility of doping by both solid and liquid dopants, which is mostly impossible for pure

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liquid- or pure solid-state fuels. The rheological properties of the slurry can be kept in the appropriate range even with a relatively large amount of additional solid or liquid components [4]. This fact opens the way for a very effective approach of fuel boosting - its metallization by aluminium powder [9–11].

The addition of metallic powder to the fuel took solid-propellant engines to a new level of efficiency [12]. A similar approach can be used for industrial fuels. However, the main difference of our approach is the usage of metal just to optimize the combustion of waste-derived fuel components (rather than as the main heating source). This method has two specific features:

(**i**) We do not need high concentrations of the metal powder, because our goal is just to boost the combustion of the CWSP composition by introducing local high-temperature inclusions.

(**ii**) Almost all the oxides of the introduced metal will be stored in the ash after the fuel combustion. It means that ash can be recycled restoring the metal.

The ash of bituminous coal typically contains up to 40% of aluminium oxides [13,14] and, therefore, this paves the way for using this very metal as a forcing dopant. The ash of the fuel doped by aluminium will contain up to twice as much aluminium oxide, which makes it a good and cheap raw material for aluminium production (similar to alumina in the conventional industrial process [15]). Therefore, our approach makes it possible to introduce the closed cycle regarding to the used metal. Actually, coal ash can contribute enough to the amount of the crude aluminium to allow a new way of transformation of the coal wastes into aluminium.

It provides a significant price reduction of the metallized fuel, making it affordable and even very attractive for certain types of coals.

The main goal of this paper is to review the prospective benefits of metallization of the pure coal–water slurries and CWSP. The ignition and combustion processes were observed by analyzing the key parameters (ignition delay time, combustion temperature, etc [16]).

2. Preparation of fuel compositions

The basic fuel composition consists of a filter cake of fiery coal (89 wt%), waste oil fuel (10 wt%) and plasticizer (1 wt%). We have chosen these components due to their availability in our region (Western Siberia) as well as for all rest parts of the World.

Filter cake is a waste which typically appears during the coal enrichment by flotation process [17]. This is fine coal powder mixed with water (particle size: ~ 100 μm; content: ~ 50 wt% of water, up to 23 wt% of bound volatiles and 27 wt% of solid carbon). Some of the main thermal and physical properties of the filter cakes we used are present in Table 1. The methods of fuel preparation are described in [4].

The petrochemical component of the CWSP was chosen similarly to that of coal, taking in account its availability and viscosity. We used the waste oil fuel, which allows keeping the viscosity of the slurry so that 2 mm droplets could be produced very easily by a Finnpipette Novus electronic batcher (using the Finntip Wide with a 1.8 mm nozzle for the viscous fuel composition to flow more easily). Finally, the droplet size variation was in range $\pm 15\%$ of the average size (2 mm). The main thermal parameters of the used oil fuel were: $T_{flash} = 477$ K, $T_{ign} = 506$ K, $T_{boil} = 588$ K, $Q_s^{comb} = 45.68$ MJ/kg. The methods of fuel preparation are described in detail in [4].

The non-organic Neolas plasticizer was used to improve the temporal stability of the fuel slurry. After a series of experiments, we found that the addition of 0.5–1 wt% of plasticizer allows the storage of the fuel for more than one week without separating the continuous and dispersed phases [18]. This plasticizer is not com-

Table 1
Physical and chemical properties of the used filter cake.

Physical properties	
Fraction of coal part in wet state, %	46.9
Combustion heat in wet state, MJ/kg	10.4
Combustion heat in dry state, MJ/kg	22.16
Yield of volatiles in dry state, %	43.11
The ash content in dry state, %	33.82
Therm. cond. (dry) at 800 K, $W/(m \cdot K)$	0.42
Specific heat (dry) at 800 K, $J/(kg \cdot K)$	1652
Temper. cond. (dry) at 800 K, cm²/s	0.0017
Chemical elements content for dry state	
Carbon weight fraction, %	75.12
Oxigen weight fraction, %	20
Hydrogen weight fraction, %	4.64
Sulfur weight fraction, %	0.23
Nytrogen weight fraction, %	0.02

bustible below 1200 K and does not have any negative properties like smell or chemical activity.

The thermophysical properties of the pure slurry were tested and they were further used as a figure of merit to analyze the properties of the metallized CWSP. Since the pure CWSP composition is a fully practical fuel that has already been tested for the industrial heating system, we concentrated on improving the combustion stability and increasing the combustion heat.

The CWSP composition was metallized by adding different amounts of PAP-2 aluminium powder (particle size up to ~ 10 μm) [19]. The metal particle size was chosen to be much less than that of coal particles for better homogenization of the slurry. The metallized slurries with weight concentrations of aluminium for 2-3-4-5% were prepared and tested.

The viscosity of pure CWSP is around 10–15 mPa·s and it goes up to 25 mPa·s for our metallized CWSP compositions. The concentration of metal powder exceeding 5 wt% leads to a significant growth of the viscosity of fuel making it inappropriate for pipeline transportation [20,21] or for most of the injection techniques used in the industrial heaters.

Final versions of the fuel compositions (including the pure CWSP) were homogenized during 15 min by mechanical mixing before experiments, although investigations could be done within a week after, without significant changes of the results. The preliminary investigations show that noticeable separation of the slurry components does not appear even after a week of storage in a hermetic glass tube [22].

3. Observation of combustion of the metallized fuel

The experimental investigations of the CWSP combustion were done by well known method of single droplet combustion [4,18,23]. The scheme of the experimental setup is presented in Fig. 1. The CWSP fuel droplet was fixed at the junction of the type-K thermocouple and was further introduced into the heat-resistant glass pipe with the hot air flow. The flow temperature and rate were controlled by a Leister LE 5000 HT flow-heater. This device allows flexible settings of the flow rate in range 0.5–5 m/s and flow temperature in range 750–1100 K. This temperature range is a very attractive from the ecological point of view. It also allows the usage of a wide variety of different wastes for future investigations of fuel compositions.

The errors in the temperature measurement are mostly random errors. The systematic errors are much smaller due to the usage of high-accuracy thermocouples (class 1), and the corresponding temperature errors are $\sim 0.004T$ in the range $T = 650–1300$ K. We made a series of three measurements at each data point to compensate for the influence of random errors. The errors induced by