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Effect of the Addition of Petrochemicals onto the Atomization and Ignition of the Coal-Water Slurry Prepared from the Wastes

Roman I. Taburchinov, Maxim V. Belonogov and Roman I. Egorov *

Tomsk Polytechnic University, 634050 Tomsk, Russia; myxa3335@mail.ru (R.I.T.); 42maxim@mail.ru (M.V.B.)
* Correspondence: rommel@tpu.ru; Tel.: +7-3822-701-777 (ext. 3485)

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Abstract: The composite quasi-liquid fuels made of different industrial waste become more and more attractive for scientists during last years. Coal-water slurry is one of the popular types of such compositions. Addition of the waste petrochemicals into the slurry allows decrease of the ignition delays of such composite for up to 27%. However, it has a non-trivial effect onto the atomization dynamics of the slurry making the size and velocity distributions of the aerosol more stable during propagation of the aerosol cloud. This, in turn, leads to more predictable ignition and combustion of the aerosol.

Keywords: coal-water slurry; coal enrichment waste; waste petrochemicals; airspraying; ignition delay time; fuel aerosol

1. Introduction

The modern strategy accepted in the most of industrial countries is switching to the green energy when production of the wastes per arbitrary unit of produced energy have to go down. This way requires the essential changes in technological chains and the first of all is a more effective usage of basic resources. It leads to smaller production of new waste with additional recycling of already accumulated waste. An application of different combustible wastes as components of the composite fuels is a very attractive way to satisfaction of the increasing appetites of modern energetics [1,2]. It allows solving both global problems of waste utilization and primary energy production simultaneously. Mixing of the different types of waste allows an effective synthesis of the properties of composition due to the combination of strong features of components with compensation of the weak points.

Thus, one of the most popular types of combustible waste are various kinds of coal enrichment waste [3,4]. There are billions of tons of such substance accumulated in numerous deposites in the World [1]. These types of waste are highly available and well investigated combustible matter but it has some very inconvenient properties that prevent the widespread application of these. High concentration of the non-combustible mineral inclusions leads to low reactivity of these combustibles and, therefore, to very long ignition delays [5,6]. The very popular way of application of the low-grade coals and coal enrichment waste is preparation of the coal-water slurry (CWS) fuel [5,7]. The combustion of such quasi-liquid fuels allows relatively low level of the production of harmful gases together with decreased level of the flying ash and dust exhausts [8,9].

The second class of widespread combustible waste are waste petrochemicals (used lubricants, oil based sediments and sludges, etc.). These types of waste mostly have a much better reactivity and calorific values than coal enrichment waste [7,10]. However, both the rheological and thermal properties of sludges are much worst than for classical oil-based fuels. The relatively low production

of such waste in comparison with waste coals makes the usage of them as main component of waste-derived fuel less reasonable.

An application of the compositions based on coals with addition of the certain amounts of water and petrochemicals (CWSP) allows making the waste-derived fuel mixture with high enough combustion temperature and relatively fast ignition [10]. Different types of coals in the deposits are conjugated with production of the sludges and filter-cakes with high enough differences of chemical content, thermal and rheological properties. Thus, the preparation of the composite fuels require an additional investigations about the final properties of the slurry [11]. The numerous papers describe the integral properties of the fuel mixture. However, scientific community mostly look onto the ignition delays of single slurry droplets under different heating mechanisms like in [12]. The atomization of composite fuels attracts high attention [13] too. However, most of papers are about pure CWS or quasi-liquid fuels made of the liquid domestic waste, oil sludges or biomass-based compositions [14,15].

The thermal effects of different additions to CWS are investigated well enough but the influence of them onto the fuel atomization is unclear. The limitations of the existing atomization techniques bind the fuel droplet sizes to slurry viscosity (and, thus, to the coal-water ratio) [16,17]. This, in turn, directly defines the combustion heat and the uniformity of the heat production. An addition of the oil-component will change the slurry viscosity as well as an adhesion of droplets and, thus, the same nozzle will make an atomization of CWSP by another manner in comparison with the CWS atomization.

The evaporation of water has strong enough influence on the evolution of the aerosol properties during propagation in free space. The evaporation of water resulting the drying of different flying droplets observed in [18,19]. Problems of droplet fragmentation under extremal thermal conditions are investigated in [20,21]. Some interesting observation of the slurry injection into the working burner were done in [22,23]. However, such works do not show in details the influence of the petrochemical components on the atomization or combustion regimes for fuel slurry.

In this paper we experimentally observed the differences of atomization of CWS and CWSP by the nozzle with radial channels with 2 bar working pressure. The obtained size and velocity distributions of the fuel aerosols are used for analysis of the propagation of the aerosol clouds in free space. The following ignition of the aerosol particles was investigated using the well tested mathematical model [24].

2. Materials and Methods

The experimental investigation of the fuel atomization was done using the setup presented in Figure 1a. Portion of the composite fuel (200 mL) was placed into the reservoir (2) and follow injected into the rectangular chamber ($75 \times 75 \times 110$ cm) through the nozzle (3) under the static 2 bar pressure made by the compressor (1). The flow of the aerosol particles was observed by the high-speed video camera Photron SA1 (4) equipped by the macro optics. The camera and light-source (5 W LED-projector (6) with 5° divergence of a light beam) can move along the axis of the cone of spray flow pattern. Therefore, one can see the evolution of the aerosol with propagation distance. The more details about the used experimental technique are shown in [16]. The essential difference from the previous experiments is usage of the nozzle with wider inner channels (diameter is about 1.5 mm). The scheme of the inner design of the nozzle is shown in Figure 1b. Such nozzle can atomize the liquids with kinematic viscosity below 3×10^{-5} m^2/s. In contrary to the case described in [16], the nozzle used in this work can atomize the CWS with concentration of solid part more than 50 wt.%. Wider channels of nozzle leads to production of bigger aerosol droplets. The nozzle used in this work allows the mean size of the aerosol about 500 μm that is just 1.5–2 times bigger than used in [16].

There were two fuel compositions used:

1. The coal-water slurry (CWS) consisting of the filter cake of the low-caking coal from the South-East Siberian region and water (40 wt.%);
2. The coal-water slurry consisting of the same filter cake and water (30 wt.%) with addition of the 10 wt.% of waste motor oil (CWSP).

The dry filter cake was milled by the rotary mill to the powder state and further sifted through a sieve with hole size about 160 μm. Therefore, the obtained powder has a mean particle size about 120 μm with the FWHM of size distribution about 80 μm. Before the experiments the powder was mixed with water during the 20 min by the mechanical mixer that produces the uniform slurry. The slurry keeps uniform state for more than two hours and, thus, it does not change the rheological properties much enough during the experiments. Preparation of the CWSP was done by the same way but the oil was mixed with water before the addition of coal. The stability of the CWSP mixture is even better than for CWS because the oil serves as plasticizer. An additional details about the physical properties of used filter-cake and petrochemicals are available in [25]. The main component of the used synthetic oil is a is polyalkylene glycol (PAG, takes about 70 wt. % or even more). The mechanical and main thermal properties of this are available from the oil manufacturer specifications but the exact chemical content is a commercial secret. For a simulation of ignition of CWSP we have assumed that oil totally consists of PAG [26,27].

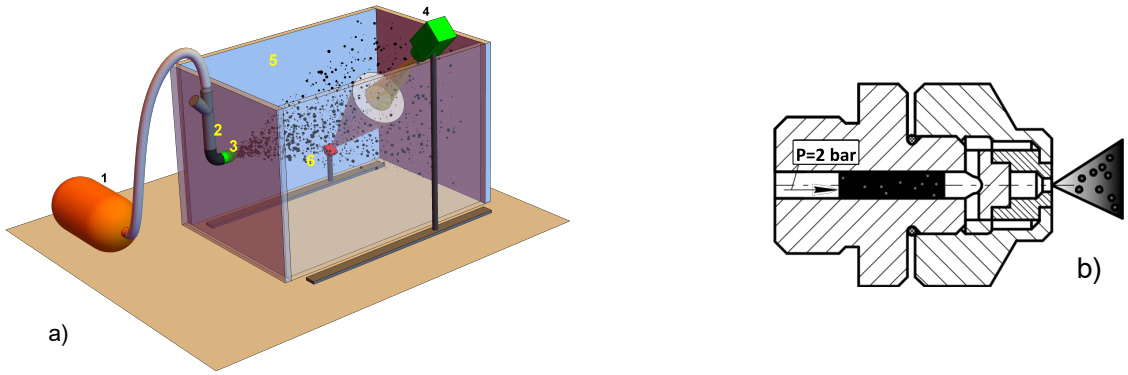

Figure 1. Scheme of experimental setup (**a**) and the cross-section of the nozzle (**b**). There are the compressor (1), fuel reservoir (2), nozzle (3), high-speed video camera (4), volume for the fuel airspraying (5), light source (6). The pressurized shot of fuel is shown in the middle of (**b**) by black.

The flying aerosol particles around the central part of the ejection cone were observed by the video camera where the video frames were captured with frame-rate about 5000 fps. It corresponds to inter-frame shift of the droplets for approx. 2 mm when droplet velocity is 10 m/s. The transversal field of view of used macro-optics was about 15 mm that allows maximal measurable velocity more than 50 m/s. The physical size of video frame together with used optics allow the spatial resolution about 12 μm/px. The recorded video was analyzed using the Particle Tracking Velocimetry (PTV) technique that allows measurement of velocities of each detected aerosol particle [28,29]. The sizes of them were analysed using the shadow photography approach within the chosen depth of field around the focal plane of macro objective. The additional details about post-processing of the recorded video are available in [16].

An accuracy of the measurements was defined by definition of the confidence intervals of sizes and velocities for three times repetition of experiments with 90% trust probability. The presented further size and velocity distributions are averaging of three measured curves for each case. The confidence intervals for mean sizes and mean velocities are about 36 μm and 0.18 m/s correspondingly.

The simulation of the aerosol particle ignition was used for estimation of the temperature dynamics on the particle surface and ignition delay times. The heat transfer equation was solved for cylindrical particles for the wide range of their sizes taking in account the radiative heat exchange

between particles and furnace walls as well as convective heat exchange between aerosol and gases inside the furnace [30]. The water evaporation was estimated according to [31]. Processes of the carbon oxidation were simulated using the Arrhenius law with previously determined activation energies and pre-exponentials [10]. The moment of heterogeneous ignition of fuel was defined as a state when the fuel surface temperature becomes higher than the environmental one and the $\partial T/\partial t$ in the subsurface layers has a jump for more than 30%. The ignition delay time was estimated as a time gap between the beginning of the particle heating and ignition moment. Mathematical model was tested by the simulation of the ignition of numerous fuels compositions (coal-water slurries, peat- and lignite-based mixtures, CWS with added fuel oil etc.) by radiative and convective heating. The simulation results were compared with experimental data with following update of the model parameters that fits model to real data.

3. Results and Discussion

3.1. Size Distribution of the Fuel Aerosol

The evolution of size distributions for aerosol particles was observed using the three different distances from the nozzle. The camera and light source were placed at 0.2 m, 0.4 m and 0.6 m from the nozzle. Thus the aerosol properties were analysed inside the range of propagation distances where the size and velocity change a lot. The further propagation goes without drastic changes of the size and velocity distribution because to the moment aerosol have dried enough even with room temperature. Together with this, particle concentration has decreased to much making interaction of them negligible.

The measured size distributions are shown in Figure 2. As one can see, the size distributions of CWS particles changes a lot during the 60 cm propagation. The distribution at 20 cm distance consists of two sharp peaks (Figure 2a). It reflects the earlier mentioned [16] process of the slurry segregation when excessive amount of water (which has weak enough adhesion to coal particles) form the small water droplets (left peak). The right peak corresponds to the slurry droplets whose size is a bit bigger than mean size of the coal particles. The right wing of the distribution shows presence of the agglomerates of coal particles sticked together by water.

Further, the propagation of aerosol leads to essential decrease of the both sharp peaks due to the drying of small droplets. The pure water droplets mostly disappear and small coal particles inside the water shell mostly determine the left side of the distribution in Figure 2b. The main lobe has maximum near 500 μm size and the 1-st moment of the distribution corresponds to approximately 550 μm. The normalization factor for vertical axes corresponds to initial number of aerosol particles at L = 0.2 m (about 200–250 thousands for one experiment). The drying eliminates smallest components of aerosol (pure water droplets) that leads to decrease of the overall particle number and, therefore, to decrease of the dominating fraction value. However, together with this, drying leads to destruction of certain amount of the agglomerates making back the increase of the smaller fraction weight. But in the case of the Figure 2c the left peak corresponds to the small slurry droplets that necessarily contain the coal particle inside.

The final shape of the size distribution for CWS shows presence of two modes of slurry droplets inside the aerosol flow: the small agglomerates of 1-2-3 coal particles and the big agglomerates containing up to dozen of them. Taking in account the decrease of the aerosol particle density due to the increase of the cloud volume, further propagation leads to self-similar decay of the distribution shown in Figure 2c.

Looking onto the size distribution for CWSP aerosol (Figure 2d–f), one can see that evolution of the aerosol with propagation distance differ a lot from the CWS case. The first principal effect of the petrochemicals is much smaller amount of the small size pure liquid droplets. The water-oil emulsion interacts with coal particles much stronger and, thus, there is much weaker segregation of slurry components. One can see, that shape of the distribution is very close at different distances. It means,

that effects of drying have much smaller influence onto the aerosol droplet sizes. The most probable size become smaller but the first statistical moment of the size distribution keeps almost constant.

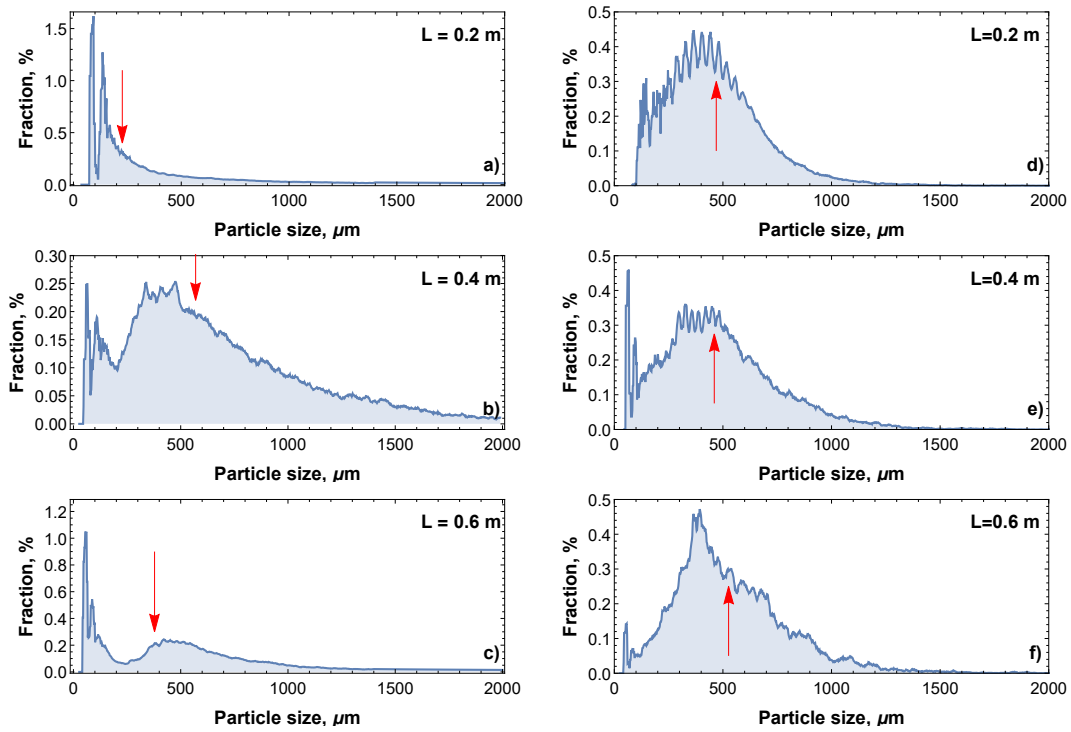

Figure 2. The measured size distributions of the aerosol particles at different distances from the nozzle for the CWS (**a**–**c**) and CWSP (**d**–**f**). The first moment of the distribution corresponds to the size shown by red arrow.

Appearance of the narrow peak at the left side of the size distribution after 0.4 m propagation of CWSP aerosol shows that effect of water evaporation is still present here. However, it does not make strong effect onto the ratio of the particle sizes.

Therefore, one can conclude that changes of the size distribution of CWSP aerosol are much more predictable. The shape of distribution does not change during the first meter of the propagation. In general, the fractions of certain sizes of CWSP aerosol particles are almost the same at different cross-sections along the flow. It simplifies the further estimations of ignition delays and heat production.

It worth noting, that after 0.6 m of propagation of aerosol flow the most probable size of CWSP aerosol particles is very similar to the most probable size of the bigger mode of CWS distribution.

An addition of the small amount of petrochemicals leads to more stable atomization of the slurry. The smaller segregation of coal and water allows better realization of the ecologically friendly combustion within wide enough range of the distances from the nozzle. Finally, the introduction of petrochemicals into the fuel composition make a strong effect onto the atomization efficiency in addition to the improvement of thermochemical dynamics of the fuel.

3.2. Velocity Distribution of the Fuel Aerosol

Looking on the velocities of the aerosol particles, one can see that used nozzle makes the aerosol flow order of magnitude faster than used in previous work [16]. It means that application the slurry with higher content of the solid part (and, thus, the higher calorific value) require longer travel of fuel inside the burners. This fact move us to conclusion that application of such fuels rather needs the swirl burner than direct flow burner.

The Figure 3a–c shows the evolution of velocity distribution of CWS aerosol with propagation for 0.6 m. One can see, that velocity distribution after 0.2 m travel of aerosol looks almost uniform in

range 0–6 m/s. The narrow peaks at the slow side show the presence of certain mechanical defects of the nozzle. The mean velocity is about 3–3.5 m/s.

Further propagation of the aerosol leads to essential changes of the velocity distribution. The mean value moves to right achieving 5 m/s. The distribution divides into two modes with relatively narrow slow lobe and wide fast one. This effect reflects the fact that big amount of small and slow particles were evaporated and the rest are faster in average. The following propagation to L = 0.6 m again make evident changes of the velocity distribution when mean velocity decreases back to 3.5 m/s. The width of the distribution goes down with a propagation distance that means that flow become more and more uniform. However, the essential changes of the most probable and mean velocities brake the uniformity of the heat distribution along the burner.

Looking onto the Figure 3d–f, one can see that velocity distribution of atomized CWSP changes by the different manner. The initial distribution (after 0.2 m propagation) consists of two nice peaks with mean velocity about 6 m/s. Further propagation of the flow goes with trivial deceleration with increase of the distribution width. After the 0.6 m of the aerosol propagation, one can see mean velocity like 4 m/s and almost the same width of the lobe like at 0.4 m/s. The absence of very fast aerosol particles (with velocities more than 8 m/s) allows decrease the probability of the sticking of fuel droplets to the walls of burner.

The influence of the nozzle defects onto the velocity distribution of the CWSP aerosol looks much weaker (the narrow peaks at the slow side does not exceed the height of the main lobe). This can be explained by the difference of the friction of slurry with the surface of nozzle and differences in adhesion of CWSP and CWS.

Therefore, an addition of the petrochemicals into the content of coal-water slurry leads to much more predictable velocities of atomized fuel with small changes of the resulting average velocities in comparison with atomized CWS.

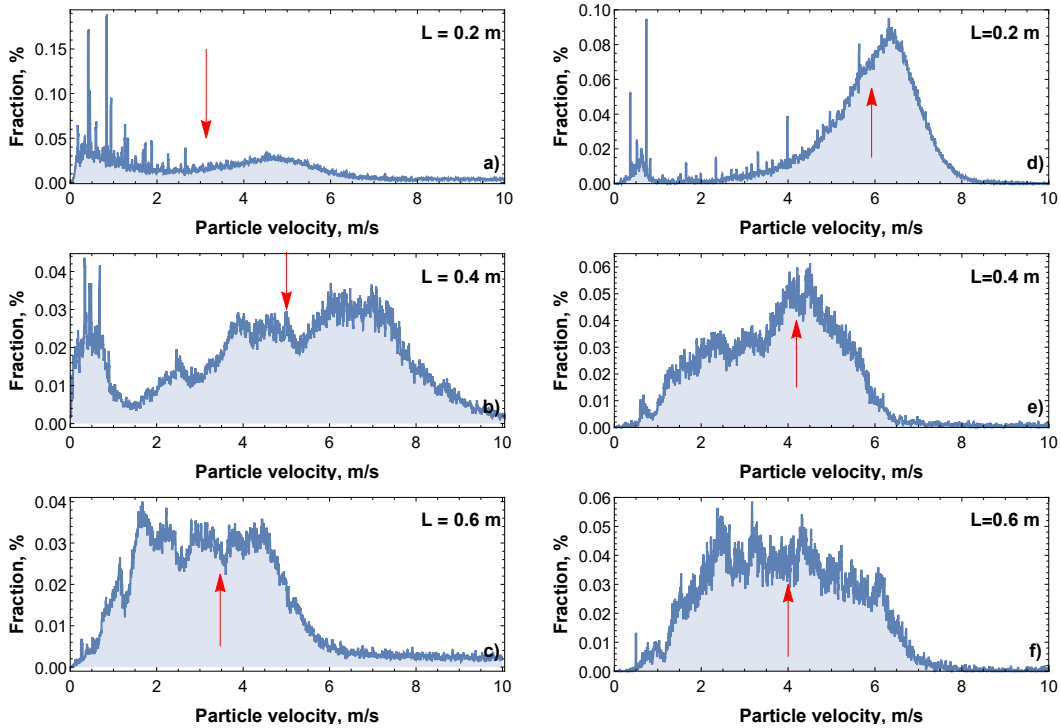

Figure 3. The measured velocity distributions of the aerosol particles at different distances from the nozzle for CWS (**a**–**c**) and CWSP (**d**–**f**). The first moment of the distribution corresponds to the size shown by red arrow.

3.3. Effect of the Petrochemicals on the Slurry Atomization

Comparison of the average values of the sizes and velocities of aerosol particles at different distances from the nozzle can show the general effect of the addition of petrochemicals onto the atomization of the slurry. Figure 4 shows the mean sizes and velocities of aerosol particles at different distances from the nozzle. One can see, that CWS sizes first grow with propagation distance and further go down to certain intermediate level. The changes of sizes of CWSP aerosol particles is much smaller. They grows a bit after 0.6 m propagation in the free space.

Looking onto the Figure 4b one can see, that changes of the mean velocities of CWS aerosol particles again looks like an oscillation. First they increases from 3.16 m/s to 5 m/s with further decrease to 3.5 m/s. This effect is conjugated with changes of the particle sizes: the drying of small particles decrease amount of the slow fraction of the aerosol. Together with this, some of the big particles become smaller due to the same drying with corresponding increase of the further deceleration due to the interaction with air.

At the same time, the CWSP aerosol shows domination of trivial deceleration due to the interaction with air on the other effects that occurs during the propagation. The mean velocity decreases from approx. 6 m/s to 4 m/s after the 0.6 m travel in free space. The final values of the mean size of CWSP aerosol particles become 1.37 times bigger than for CWS aerosol. The final values of the mean velocity of CWSP aerosol become 1.13 times higher than for CWS one.

It worth noting that comparison of the nozzle flow rate for these two fuels show that CWSP allows approximately 10% advantage of the volume rate (11.2 mL/s for CWS and 12.1 mL/s for CWSP). Taking in account that density of the CWSP is just 2–3% smaller, one can see that weight flow rate of CWSP is clearly higher.

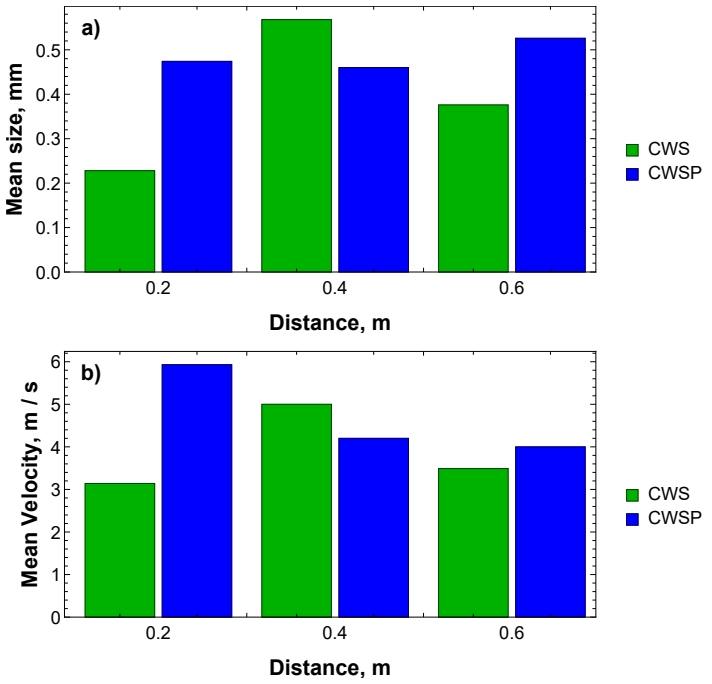

Figure 4. The mean values for sizes (**a**) and velocities (**b**) of the aerosol particles at different distances from the nozzle.

4. Ignition and Combustion of the Aerosol Particles

4.1. Effect of Petrochemicals on the Ignition Delay Time

The inductive ignition of the slurry fuel was investigated using the well tested mathematical model. The Figure 5 shows the calculated dependence of the ignition delay time (IDT) on the particle size for burner temperature about 873 K. One can see, that addition of the petrochemicals allows approximately 27% decrease of IDT for small particles and more than 10% for big particles. It is clear, that partial replacement of water by combustible liquid leads to proportional decrease of time needed for fuel drying. Thus, the 10% acceleration of ignition of big droplets can be explained from this point of view. Together with this, the much stronger acceleration of ignition of small droplets goes from contribution of combustion of additional volatiles produced during the heating of the waste oil.

Taking in mind the presented in Section 3, one can make conclusion that ignition of the CWSP particles in general will accelerate for less than 17%. The CWS almost always contains more small particles and this fact does not allow to use the maximal advantages of the IDT decrease. Together with this, the aerosol of CWSP does not contain valuable amounts of particles whose sizes are bigger than 1100 μm.

Looking on the most probable aerosol particle sizes, the average IDT for CWSP will achieve 1.1–1.4 s, whenever the CWS particles will ignite in the range 0.7–1.6 s. The wide range of ignition delays for CWS make it very inconvenient for most of the burners because the corresponding travel length of the injected fuel (according to mean velocities) is too long. The trend of particles deceleration with travel distance tells us that velocity of CWSP will decrease fast enough. The CWS particles will ignite within the range 1.3–1.7 m during all this way.

The CWSP promises much more convenient case: the travel length inside the furnace will be about 1.5–1.6 m. The most of the aerosol particles will ignite to the middle of this range. Therefore, an addition of the petrochemicals allows certain decrease of the overall required travel distance inside the hot environment of burner. Together with this, it essentially decrease the length of the way where aerosol will ignite (for a 4 times) with corresponding local jump of furnace temperature.

Taking into account these distances, it is fully possible to use the measured particle sizes for the 0.6 m distance from the nozzle as an actual sizes to the ignition moment.

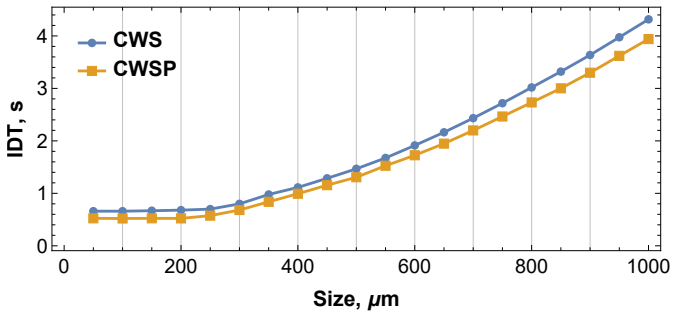

Figure 5. Calculated dependence of the ignition delay time on the particle size for CWS and CWSP when the furnace temperature is about 873 K.

4.2. Temperature Dynamics of Aerosol Particles

Figure 6 shows the dependence of the surface temperature of CWS and CWSP particles under the radiative and convective heating inside the furnace with temperature about 873 K. One can see, that both mean and most probable sizes of aerosol particles allow very close maximal combustion temperatures. The difference of this maximum values for the CWS and CWSP does not exceed 3–4%. However, the duration of the particle combustion when surface temperature exceeds the environmental one grows with particle size. One can see, that for most probable sizes of aerosol particles (orange and red curves) the time of heat production is quite close. It means that atomized CWSP with size

distribution similar to shown in Figure 2f will produce the uniform enough heating. The CWS whose size distribution has two peaks will make pulsed heat production when small particles will burn quickly and the big particles will ignite after certain delay.

All mentioned means that addition of the petrochemicals leads to more uniform combustion due to the better size and velocity distribution of the aerosol together with a faster ignition of the particles of certain size.

The presence of small particles in the cloud of atomized CWS after 0.6 m propagation means certain simplification of the initial ignition. These small fractions with very short IDT can serve as activated fuel with higher reactivity. As result, starting from the feeding of burner by CWS one can switch further to CWSP after the beginning of more or less stable combustion. The usage of the CWSP for regular feeding of the burner allows 10–13% higher calorific value of the fuel together with all presented benefits of the atomization.

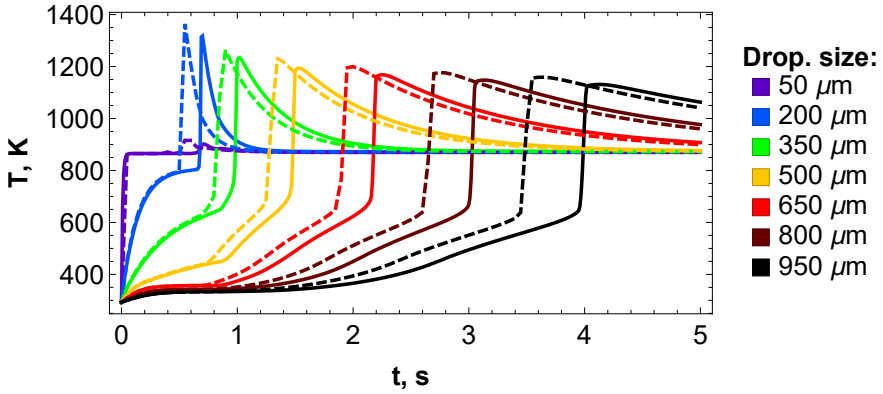

Figure 6. The surface temperature dynamics for aerosol particles with different size. The solid lines correspond to the CWS and the dashed to the CWSP.

5. Conclusions

The effect of the addition of waste petrochemicals to the coal-water slurry has two branches:

- it introduce much more uniform size and velocity distribution of fuel aerosol during the first meter of its propagation when main changes of parameters of aerosol occurs. The used nozzle produces in average 0.5 mm droplets that keep size very stable;
- petrochemicals allows up to 27% faster ignition of the CWSP aerosol particles relatively to CWS particles of the same size;
- the peak temperature of combustion of the CWSP aerosol is 3–5% higher than for similar droplets of CWS.

The integral effect consists in decrease of the ignition delays together with essential decrease of the required travel distance of fuel particle inside the hot environment to the moment of ignition.

However, the presence of small fractions in the typical clouds of the pure CWS can serve as a factor ultimately decreasing the IDT. Therefore, it can be useful at the basic ignition of the burner with feeding by composite waste-derived fuel.

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Abbreviations

The following abbreviations are used in this manuscript:

CWS	Coal-water slurry
CWSP	Coal-water slurry with petrochemicals
IDT	Ignition Delay Time
PAG	Polyalkylene glycol
PTV	Particle Tracking Velocimetry

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