Contents lists available at ScienceDirect

Fuel Processing Technology

Research article

The ignition dynamics of the water-filled fuel compositions

Roman I. Egorov[*], Dmitry V. Antonov, Timur R. Valiullin, Pavel A. Strizhak

National Research Tomsk Polytechnic University, 30 Lenin Avenue, Tomsk 634050, Russia

A R T I C L E   I N F O

A B S T R A C T

Various fuel composites became popular for a last decade because smart mixture of different combustibles allows effective minimization of the negative features of components. In this paper we have observed the influence of water evaporation on the different stages of ignition of the waste derived coal-water slurry with addition of the waste petrochemicals. It was shown that the gas-phase ignition stage and heterogeneous ignition stage of the slurry have the increasing time-separation (from 4 to 50 ms) with a growth of the furnace temperature after 1000 K. It happens because the peak of water vaporization in the volume of fuel shifts closer to the moment of ignition with furnace temperature increase. As result, an additional fuel heating is required before the heterogeneous ignition. The volume power density of volatiles combustion around the fuel droplet grows for 30–40 times with furnace temperature changes from 870 K to 1070 K. However, combustion of the volatiles does not produce heat enough for the immediate beginning of the stable heterogeneous ignition when the water content is about 30–40%. The obtained results can be used in future for an effective optimization of the ignition of the water-filled fuels as well as for a choice of the most effective and ecological combustion regime.

1. Introduction

During the last decades, different types of the composite organic fuels (especially the waste-derived compositions) became very popular in the industrial applications. Mixing of various well-known components allows to get the fuels with pre-defined properties that are desired for particular applications from the ecological, economic and energetic point of view. In this way, the weak sides of pure one-component fuels can be compensated by features of additives [1–4].

Some of these fuels are mixtures of only liquid or only gas components and their ignition goes in the single phase state. Such fuels start to burn in the gas state and these processes are quite good investigated [5–7]. However, there are the huge variety of the perspective heterogeneous compositions (liquid & solid) used in different industrial applications for years. The complicated set of processes starts at the ignition of such fuels making the optimization of ignition parameters very complicated. The coal-water slurry (CWS) is the typical example of such well-known fuel whose properties are not absolutely clear still. Different additives together with different external conditions can change the ignition mode very much [8,9]. The presence of big amount of the combustible volatiles [8,10] in composition of the CWS with addition of petrochemicals visually leads to the certain acceleration of fuel ignition. Together with this, the presence of water makes the ignition process less predictable due to the fact that its evaporation can consume huge amount of the heat making longer the ignition delay

time. The beginning of the massive steam production is defined by thermal conductivity and heat capacity of the fuel as well as by oxidation processes going inside it. Prediction of the optimal regimes of an ignition requires clear understanding of the undergoing processes.

The waste-derived fuels which are of interest for different scientists during the last decades represent the good example of such multiphase fuels (slurry, emulsions) [8]. They typically contain the low-grade coals [11] whose ignition is optimized by an addition of waste petrochemicals and, at the same time, decelerated by big amount of water. Generally, water gives a decrease of the combustion temperature which in turn decreases the greenhouse gases production improving the ecological effect of the fuel combustion [12].

In this paper we try to clarify the influence of water evaporation onto the ignition delay of the solid part of the waste derived coal-water slurry (with added waste petrochemicals) for the furnace temperature range 870–1070 K. The dynamics of the ignition and combustion of CWS is a subject of numerous investigations [9,10,13-15] but features of different ignition stages were not investigated in details still. We have used the results of computer simulations together with experimental data to define the contribution of the major thermal processes at the stages of ignition of multiphase fuel composition.

Our second goal is determination the influence of volatiles on the ignition of the solid part of fuel.

* Corresponding author.
  E-mail address: rommel@tpu.ru (R.I. Egorov).

Table 1
Physical and chemical properties of the fuel components.

Filter cake	
Fraction of coal part at wet state, wt%	62.1
Combustion heat at wet state, MJ/kg	9.46
Combustion heat at dry state, MJ/kg	15.23
Yield of volatiles at the dry state, wt%	14.8
The ash content at the dry state, wt%	50.89
Carbon content at dry ash-free state, wt%	87.47
Hydrogen content at dry ash-free state, wt%	5.039
Nitrogen content at dry ash-free state, wt%	2.15
Sulfur content at dry ash-free state, wt%	0.444
Oxygen content at dry ash-free state, wt%	4.77
Therm. cond. (dry) at 400 K, W/(m·K)	0.49
Specific heat (dry) at 400 K, J/(kg·K)	2435.5

Waste motor oil	
Density at 293 K, kg/m^3	871
Humidity, wt%	0.28
Ash content, wt%	0.78
Ignition point, K	491
Combustion heat, MJ/kg	43.98
Evaporation heat, MJ/kg	0.178
Therm. cond. at 400 K, W/(m·K)	0.107
Specific heat 400 K, J/(kg·K)	1760

Waste turbine oil	
Density at 293 K, kg/m^3	868
Humidity, wt%	< 0.01
Ash content, wt%	0.03
Ignition point, K	466
Combustion heat, MJ/kg	44.99
Evaporation heat, Mj/kg	0.198
Therm. cond. at 400 K, W/(m·K)	0.167
Specific heat at 400 K, J/(kg·K)	1974

Waste fuel oil	
Density at 293 K, kg/m^3	1000
Humidity, wt%	6.12
Ash content, wt%	4.06
Ignition point, K	513
Combustion heat, MJ/kg	39.41
Evaporation heat, MJ/kg	0.193
Therm. cond. at 400 K, W/(m·K)	0.007
Specific heat at 400 K, J/(kg·K)	2177

2. Materials and methods

2.1. Preparation of the fuel compositions

We have prepared the fuel compositions with a high volatile content. Using such fuels, we can distinguish the contribution of volatiles into the ignition as well as an effect of water. The coal component was a filter cake of low-caking coal which contains less than 15 wt% of volatiles in dry state. An essential part of the combustible volatiles in the composite fuel was derived from the petrochemical component. We have prepared three fuel compositions using the filter cake and three types of additives (10 wt% of the waste motor oil, turbine oil and waste fuel oil correspondingly). These liquids produce different amount of combustible volatiles due to differences of the evaporation rate and heat capacity. The filter cake by itself contains approximately 40% of water and all rest is a milled coal with particle size ~ 100 μm. Some parameters of the solid and liquid combustible components are shown in Table 1.

Thus, we have three heterogeneous fuel compositions:

1. the first one has a high evaporation rate of the liquid part with moderate level of the thermal conductivity (filter cake & motor oil);

2. the second has an essentially lower evaporation rate but the higher thermal conductivity of the liquid part (filter cake & turbine oil);

3. the third one has low evaporation rate together with the low thermal conductivity (filter cake & fuel oil).

These samples allow us an easy visualization of the effects of the volatiles release and their gas-phase ignition. The big amount of water inside the sample leads to certain deceleration of the temperature growth during the fuel heating as well as to decrease of the combustion temperature.

Homogeneity of the samples was very high due to the durable processing with mechanical homogenizer. Our previous experience [8,13,14] tells that three-component fuel compositions keep stable properties during 2–3 days, so there are not any essential problems for its usage during this time.

2.2. Observation of the ignition

The experimental observation of the different ignition stages of the composite fuel was done by a non-trivial way: the fuel portion (droplet with diameter ~ 2 mm) was introduced into the cylindrical muffle furnace (Nabertherm R 50/250/13) by the motorized translation stage. The process of ignition was observed from the another face of the furnace cylinder by the high-speed color video camera Phantom V411 (as it is shown in Fig. 1). The duration of the fuel injection process is approximately ten times shorter than the heterogeneous ignition delay time. Therefore, the ignition goes in the steady state atmosphere without ordered movements of an air (just diffuse effects present). This fact allows us to see the gas-phase ignition stage very well. The color sensitivity of the camera gives us the possibility of easy distinguishing of the combustion of volatiles against a bit colder heterogeneous combustion on the droplet surface. Keeping in mind that the calorific value of the volatiles is ~ 2 times higher than for coal coke, we can estimate the wavelength difference of the flame light according to Stefan-Boltzmann and Wien laws. The hot flame of the volatiles will give us the approximately 20% shorter wavelengths than colder coke flame.

The frame resolution (1024 × 768) and the frame rate (2500 fps) allow to see these stages of the ignition in details. The muffle furnace can keep the exact temperature value in range from the minimal ignition threshold (~ 850 K for these compositions) and up to 1500 K. However, we have used the temperature range from 873 K to 1073 K because lower temperatures are below the stable fuel ignition threshold. On the other hand, the differences of the ignition delay time of different fuel compositions almost vanish when the temperature of the environment is higher than 1000 K. It means that most of the chemical reactions starting in the fuel during heating achieve the fastest rate. The same is true for the phase transition processes that go there in parallel with chemical reactions. It looks that differences of the ignition processes will degenerate at higher temperatures to the common sequence of states that is very similar for different fuel compositions.

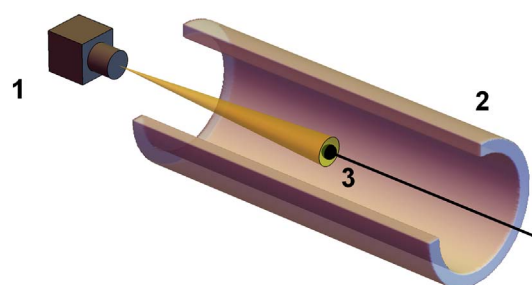The chosen frame rate of the camera allows the 0.4 ms resolution for

Fig. 1. Scheme of the experiment. There are the high-speed video camera (1), cylindrical muffle furnace (2) and fuel droplet at the holder (3).