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The Role of Carbon in Explosion of Dust-air Mixtures

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Several grams of flammable dust mixed with air can cause a large explosion with severe consequences. In this study, dust mixtures explosion tests were performed in constant volume 0.02 m3 spherical vessels. 19 pressure-time curves were recorded. The effects of carbon amount in sample molecules on burning velocity were investigated for coal, biomass pellets, and ash-air dust mixtures. The most important results are the values of ash sample burning velocities. The results could be used for a hierarchical view of tested mixtures and for preventing and mitigating dust-air explosions in a given application.

1. Introduction

As a starting point before this case study one can consider the issue that the fly ash is not explosible. It is because of the convention wisdom that flies ash doesn’t explode because ash is material left over after combustion. The combustion process in small-scale appliances for household heating is always incomplete. An incomplete combustion process means that there is a mass concentration of unburned carbon in fly ash. (Amyotte, 2012) Dufaud et al. (2012) highlighted the influence of the pyrolysis step in organic dust explosions. All experiments have been carried out on wheat starch powders and on their pyrolysis gases. Starch pyrolysis has been studied and representative composition of the pyrolysis gases has been used for explosion tests. Torrado (2017) investigated the effect of carbon black nanoparticles on the explosion severity of gas mixtures. Tests have been performed in a flame propagation tube and in the standard 20 L explosion sphere. It appeared that the carbon black nanoparticles insertion increases around 10% the explosion severity for lean methane mixtures. The present paper compares the laboratory-scale testing of coal-air, biomass pellets-air, and fly ash-air mixture based on the explosion parameters obtained in a standard 0.02 m^3 explosion chamber using the two 5-kJ chemical igniters.

2. Experiment

The experiments have been performed in a 0.02 m^3 constant volume stainless steel double wall vessel of spherical shape (OZM Research, s.r.o) adopted for the dust-air mixture experiments. The dynamic explosion pressures have been recorded by pair of piezoelectric pressure sensors (model 701A, Kistler) and with a transducer sensor charge amplifier (model 5041E1, Kistler) combined with Programmable logic controllers (model 5073A211, Siemens). (Skřínský and Ochodek, 2019) The ash sample was produced by combustion equipment, a prototype of an automatic wood pellet stove further called Prototype 1. Due to a fact that the stove is still in the process of development, there are no established parameters for nominal power and so on. The settings of the control unit for fuel adding were always the same during the tests: 10/10 (s/s) adding/pause. The amount of added fuel in 1 h was investigated experimentally. This value and the known net calorific value of used fuel determine the operating input power of the stove, P = 7 kW. Hot flue gases are transmitting their heat energy to the air in a flue gas-air heat exchanger above the combustion chamber. Heated airflow was provided by an air fan.

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(Ryšavý et al., 2019) Both experimental setups are schematically introduced in Figures 1-2. During the combustion tests, the Pt-based honeycomb catalyst was installed right inside the flue gas duct at the stove outlet. Fly ash settled on the catalyst was gathered every 40 hours of the stove operation.

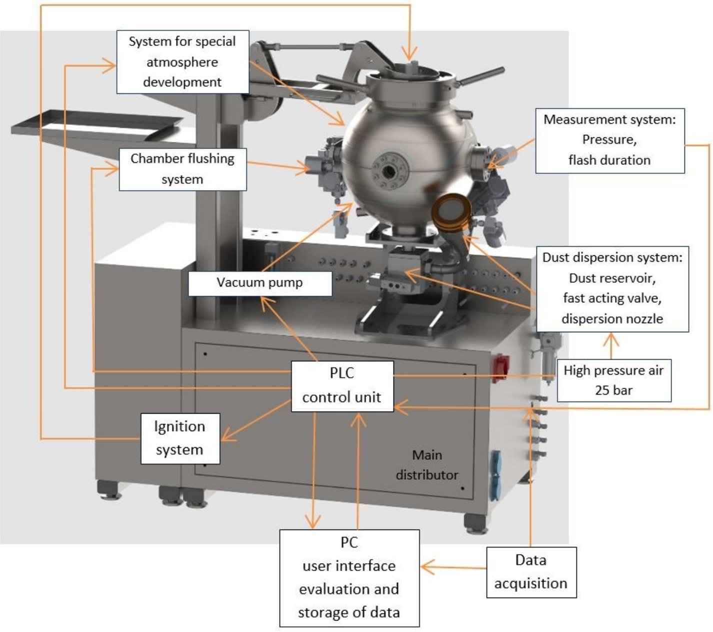

Figure 1: The standard 20L-sphere

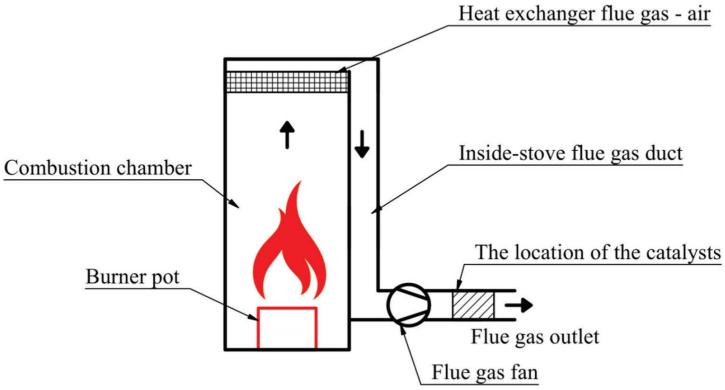

Figure 1: Sketch of used automatic stove.

Figure 2: The wood pellet stove set-up (Ryšavý et al., 2019)

2.1 Procedure

The methodology is applied to investigate the explosion severity characteristics is based upon the combination of three standard procedures and one recently published: the European Standards EN 14034-1+A1 (2011), EN 14034-2+A1 (2011), and operating procedure for Round Robin (BAM, 2021). The latter one allows the explosion of the dust-air mixture parameters measurement to adapt for hybrid mixtures studies. The illustrative results of Pre-Tests – the leakage rate and the post-injection pressure drop – for standard 20L-sphere are shown in Figures 3-4.

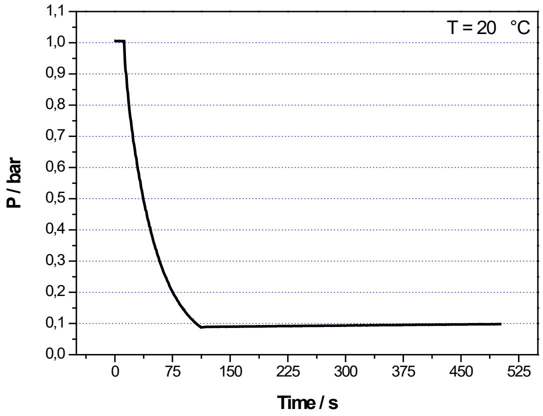

Figure 3: Leakage rate (lower than 1 mbar / min.)

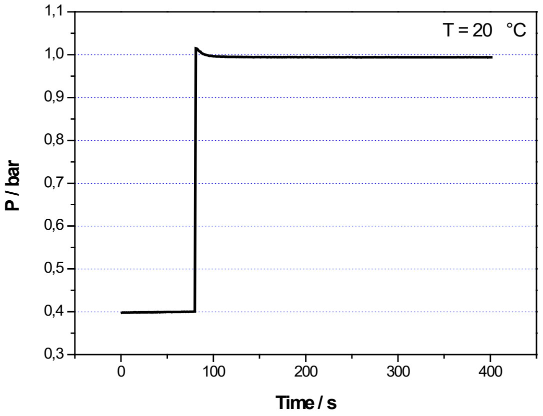

Figure 4: Post-injection pressure drop

2.2 Analysis

The accurate dust particle size distribution was determined as a mean from three independent measurements by the laser particle size analyzer a type 1090 CILAS. Moisture content was measured using a Mettler Toledo type 256 moisture analyzer. The elements' composition in the raw state was determined by LECO CHN 628 and LECO 628 S. The results of the dust sample analysis are listed in Table 2-4.

Table 2: Particle size distribution

Parameter	Coal µm	Pellets µm	Ash µm
Diameter at 10%	0.2	17.5	2.4
Diameter at 50%	16.1	138.6	56.9
Diameter at 90%	317.9	406.7	224.6
Mean diameter	79.3	181.0	87.7

Table 3: Moisture content

Parameter	Coal Vol. %	Pellets Vol. %	Ash Vol. %
Moisture	1.0	6.0	0.3

Table 4: Elements' composition in raw state

Element	Coal Vol. %	Pellets Vol. %	Ash Vol. %
Carbon	75.1	47.5	7.9
Hydrogen	5.8	5.7	0.6
Nitrogen	0.9	<0.2	<0.2
Oxygen	10.9	40.3	10.9
Sulphur	1.0	<0.2	<0.2
Ash	5.3	0.3	80.2

3. Calculation

The role of propagating flame thickness is accessed via maximum rate of pressure rise – the volume of the vessel-dependent characteristic and is described in Equation 1.

The deflagration index was defined as:

$$K_G = \left.\frac{\mathrm{d}P}{\mathrm{d}t}\right|_{\max} \sqrt[3]{V} \tag{1}$$

4. Results and discussion

4.1 Explosion parameters

In the first step, the maximum explosion pressure of steady-state coal–air and biomass-air mixtures were measured in a wide range of equivalent ratios. In order to obtain properly averaged results, each test was repeated 3 times and the average is plotted in the pressure-time curve. In the second step, the main input parameters for Equation 1 in terms of the maximum rate of pressure rise have been determined. The examples of measured data for studied materials are depicted in Figures 5-8.

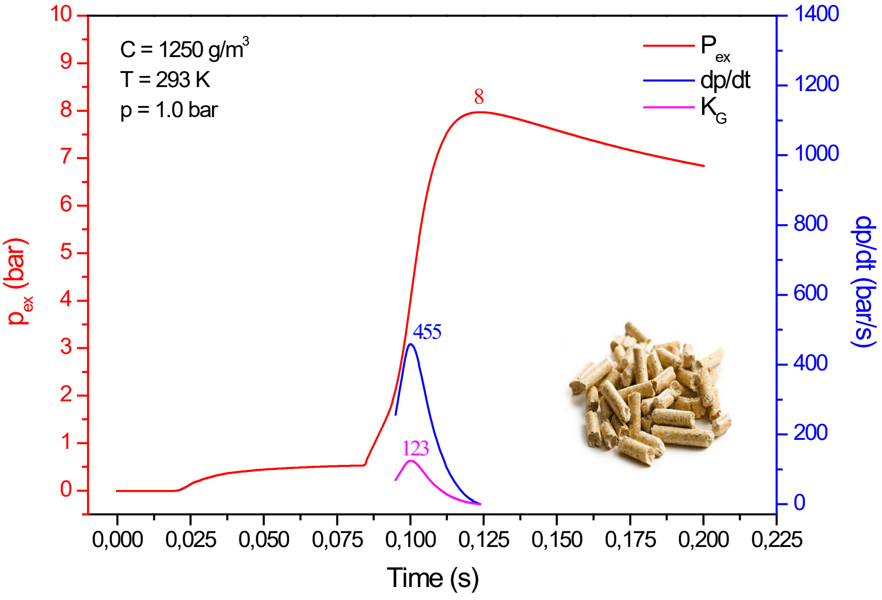

Figure 5: p_{ex} and dp/dt for biomass pellets in 0.02 m^3

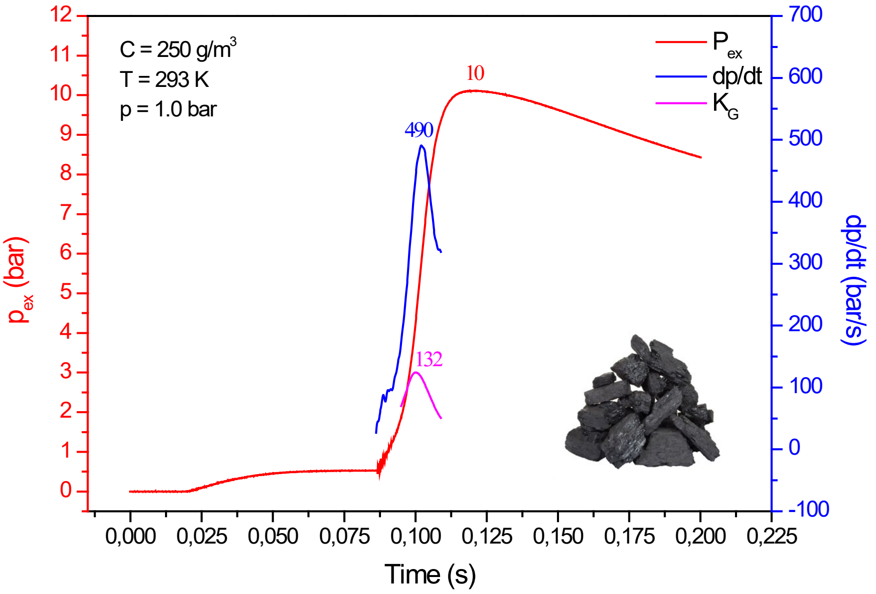

Figure 6: p_{ex} and dp/dt for coal in 0.02 m^3

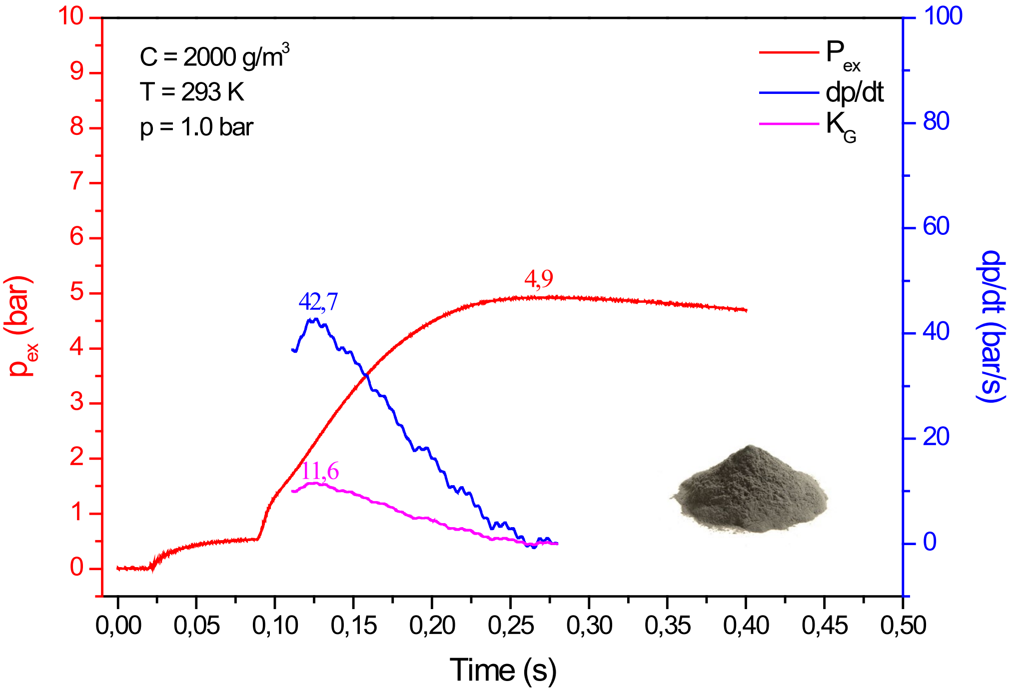

Figure 7: p_{ex} and dp/dt for ash in 0.02 m^3

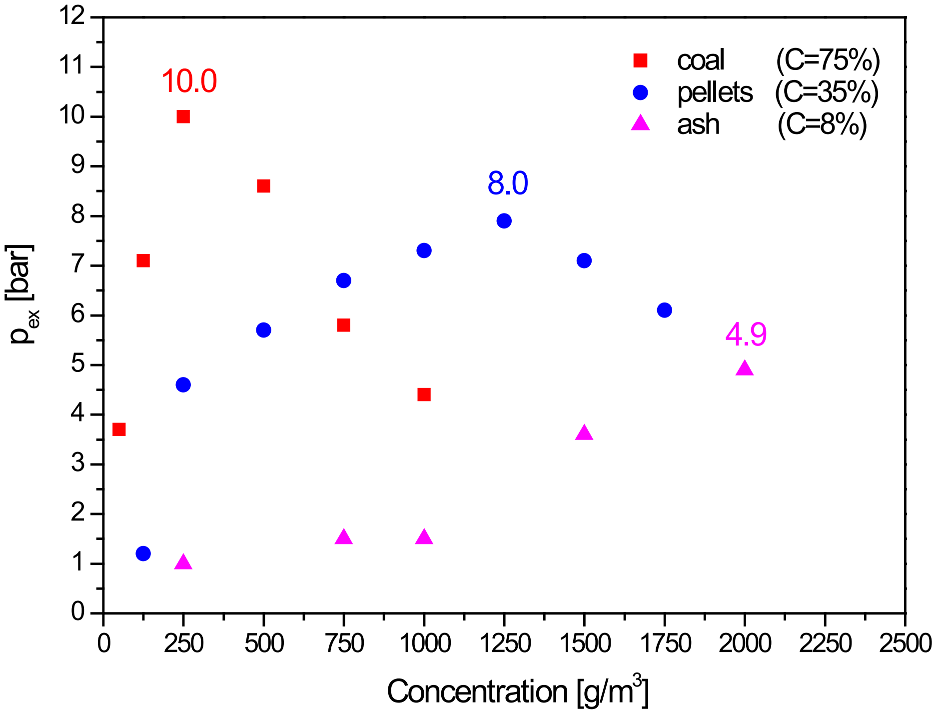

Figure 8: Comparison of p_{ex} for coal, pellets, and ash in 0.02 m^3

5. Conclusions

Increasing the mass concentration of the carbon in the sample and creating a dust-air mixture has affected the explosion pressure with the difference higher than 10 % and shifted the maximum values of mass concentrations from 250 g/m^3 for 75 % of carbon to more than 2000 g/m^3 for 8 % of carbon in the material.

The main conclusions:

1) Accurate determination of maximum explosion pressure and deflagration index at atmospheric temperatures and pressure for concentrations C = 250 – 2000 g/m^3.
2) The maximum values of explosion pressures and rates of pressure rise.
3) The values of maximum explosion pressure show that the ash is two times less dangerous than the coal-air dust at given experimental conditions.

In real conditions of small-scale solid fuel combustion appliances with installed catalyst is necessary to clear the catalyst by compressed air right inside the flue gas duct from the settled ash regularly. More frequent cleaning reduces the risk of explosion by lowering the actual amount of fly ash settled on the catalyst. Frequent cleaning of the catalyst is also necessary from the clogging of the catalyst’s point of view. From the ash composition point of view, improvement of the combustion process (design of the combustion chamber, fuel/air ratio, etc. could lead to reduction of unburned carbon in fly ash.

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Nomenclature

K_G – deflagration index, bar.m/s
p – pressure, N/m^2
p_0 – initial pressure, N/m^2
t – time, s
T – temperature, K
V – vessel volume, m^3

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