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OXY-COMBUSTION OF DIFFERENT COALS IN A CIRCULATING FLUIDIZED BED

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ABSTRACT

Combustion of three Polish and one South African bituminous coal particles in air versus O₂/CO₂ mixtures with oxygen concentrations in the range from 21% to 60% vol. was conducted at temperature of 850°C in a 12 kW bench-scale CFB combustor. Combustion in air was proceeded at ~50°C higher centre temperatures and was slightly shorter in time compared to combustion in O₂/CO₂ mixture with 21% vol. O₂. Larger heat capacity of CO₂ compared to that of N₂ also retards the ignition of volatiles in O₂/CO₂ mixtures with 21% O₂. However, when the concentration of oxygen in O₂/CO₂ mixtures is larger than 30%, the ignition time decreases and surface and centre temperatures increase significantly with increasing O₂ content.

INTRODUCTION

Nowadays, greenhouse gases emissions from coal-fired systems, particularly CO₂, become more and more important. Oxy-fuel combustion is one of the promising options for power generation with carbon dioxide capture. This technology can reduce significantly emissions of NO_x and improve the thermal efficiency of the combustion process through the reduction of flue gas volume. In the oxy-fuel combustion, coal particles are burnt in a mixture of pure oxygen and recycled flue gas. Because nitrogen is eliminated from the oxidizing gas, the flue gas leaving the combustion chamber is highly enriched in CO₂ which means that the combustion process takes place in an O₂/CO₂ environment. Partial recycling of flue gas helps to control the flame temperature in the combustion chamber. Extensive studies in both pilot-plant and lab scales have pointed out the pronounced influence of gas composition (air versus O₂/CO₂) on coal combustion performance. The heat transfer and temperature distribution in a furnace are greatly affected by the large specific heat capacity of CO₂. Coal ignition is delayed in O₂/CO₂ in comparison to in O₂/N₂ with the same O₂ concentration. To match the flame/particle temperature in air, a large amount of O₂ in CO₂, typically around 30%, is required. Coal conversion rate, char properties, and reactivity are also affected by the replacement of air with an O₂/CO₂ mixture, Zhang et al. (1). Buhre et al. (2) and Toftegaard et al. (3)

summarized the literature on oxy-fuel combustion of pulverized coal and discussed a number of operational concerns, including ignition, heat transfer, environmental issues and flame stability. Oxy-fuel combustion has now been well studied for pulverized coal combustion, but to date has received relatively little attention for oxy-fuel circulating fluidized bed combustion (CFBC), Jia et al. (4). Work in this field has been conducted by: Foster Wheeler Energia Oy and VTT (5), ALSTOM (6), CANMET (4) and Czestochowa University of Technology (7).

In the present work, oxy-fuel CFB combustion tests were conducted in a 12-kW bench-scale CFB combustor. The main objective of this study is to investigate the combustion behaviour of three Polish and one South African bituminous coal particles, in air and O₂/CO₂ mixtures, in terms of particle temperature profiles, ignition time, devolatilization time and the total combustion time.

EXPERIMENTAL

Oxy-CFB Combustor

Oxy-fuel combustion tests were conducted in a 12-kW bench-scale CFB combustor shown schematically in Figure 1. The bench-scale CFBC consists of a combustion chamber (1), a cyclone (2) a downcomer (3) and a loop seal (4). The electrically-heated rectangular combustion chamber (riser), 680×75×35 mm, is the main component of the unit. The front wall of the riser is made of transparent quartz through which the combustion process can be directly observed.

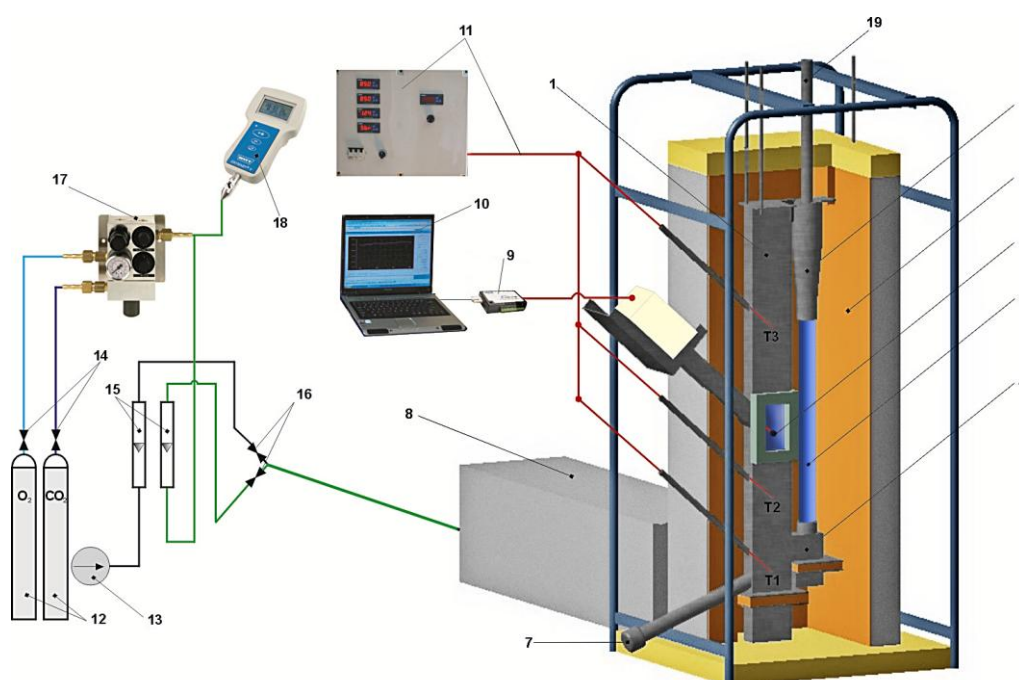


Fig. 1. Schematic diagram of the experimental apparatus for oxy-CFB combustion

1-combustion chamber, 2-cyclone, 3-downcomer, 4-loop seal, 5-coal particle, 6-insulation, 7-drain valve, 8-preheater, 9-card, 10-computer, 11-temperature measurement and control system, 12-gas cylinders, 13-air compressor, 14-pressure regulators, 15-rotameters, 16-valves, 17-mixer, 18-gas analyser, 19-ventilation duct, T1-T3-S-type thermocouples

Particles of silica sand between 100 and 400 μm , with $d_{50}=210 \mu\text{m}$ (d_{50} , median sand particles diameter, represents the size at which 50%, of the sand particles, by weight, are smaller than the specified diameter), constitute the inert bed (see Figure 2 for the particle size distribution). Total mass of circulating solids is 0.3 kg. The gases to make up gas mixtures are supplied from cylinders (12) to a mixer (17) and then transferred via a preheater (8) directly into the combustion chamber. Flow rates of gases are controlled by valves (16) and measured by rotameters (15). During combustion tests, the superficial gas velocity was kept at a constant level of about 5 m/s. The temperature was held at 850°C by means of microprocessor thermoregulators (11). S-type thermocouples (T1–T3) measured the temperature at three different levels inside the combustion chamber with an accuracy of $\pm 2^\circ\text{C}$.

A single coal particle (5) was introduced into the combustion chamber and positioned stationary in the bed. To measure the temperatures in the centre and at the surface of the coal particle a special stand was constructed. It provides a support for two S-type thermocouples. The tip of the first thermocouple was located inside the particle, while the second thermocouple measured the surface temperature and served as a basket in which the coal particle was placed. The thermocouples were connected via a card (9) to a computer (10) in order to record the temperature measurements. Ignition time and devolatilization time were measured by stopwatch with an accuracy of 0.1s. The intraparticle temperature, the surface temperature, ignition time and devolatilization time were measured simultaneously.

The experiments were carried out in air (base case) and mixtures of O_2/CO_2 with oxygen concentrations in the range from 21% to 60% vol. Video and digital cameras were used to record the progress of combustion.

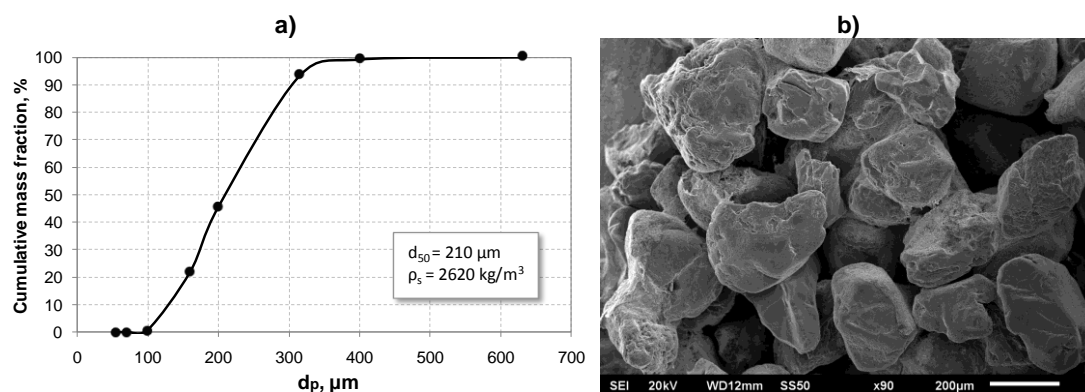


Fig. 2. The bed material (silica sand): a) particle size distribution, b) SEM picture

Coals Tested

Particles of three Polish and one South African bituminous coal were used in this study. Table 1 shows proximate, ultimate and petrographic analyses of these coals. Spherical 10-mm particles were produced from coal lumps through mechanical grinding.

Table 1. Proximate, ultimate and petrographic analyses of the coals tested

Coal	A	B	C	D
	Polish	Polish	Polish	South African
Proximate analysis (% , air-dried basis)				
Volatile Matter	30.9	30.9	28.9	23.7
Moisture	2.7	4.3	10.1	3.8
Ash	2.4	8.2	11.1	25.0
Fixed carbon	64.0	56.6	49.9	47.5
Calorific value (HHV), MJ/kg	32.38	31.31	24.66	22.44
Ultimate analysis (% , dry, ash-free basis)				
Carbon	83.73	82.97	75.94	81.90
Hydrogen	4.59	5.14	4.59	3.44
Nitrogen	1.34	1.28	1.48	2.44
Sulphur	0.33	0.68	2,17	2.71
Oxygen (by difference)	10.01	9.93	15.82	9.51
Petrographic analysis, %				
Vitrinite	52	88	59	14
Liptinite	9	2	12	0
Inertinite	39	6	21	68
Mineral matter	0	4	8	18

RESULTS AND DISCUSSION

Results of proximate and petrographic analyses (Table 1) reveal that ash and inertinite (maceral that is less reactive than vitrinite) contents in the South African are much higher than those in Polish coals. Therefore, it can be expected that the combustion behaviour of these coals may differ significantly. Thus, the main objective of our study was to investigate the combustion behaviour of these coals, in air and O_2/CO_2 mixtures, in terms of particle temperature profiles, ignition time, devolatilization time and the total combustion time.

Figure 3 shows temperatures measured at the surface and in the centre of C and D coal particles burned at $850^\circ C$ in air and in O_2/CO_2 mixture with 21% vol. O_2 . In both cases, after an initial delay, the centre temperature exceeds the surface temperature and stays approximately $100^\circ C$ during the course of combustion. Lower surface temperatures can be explained by intensive heat transfer between burning coal particles and bed material. Combustion in air proceeded at $\sim 50^\circ C$ higher centre temperatures and was slightly shorter in time compared to combustion in O_2/CO_2 mixture with 21% vol. O_2 .

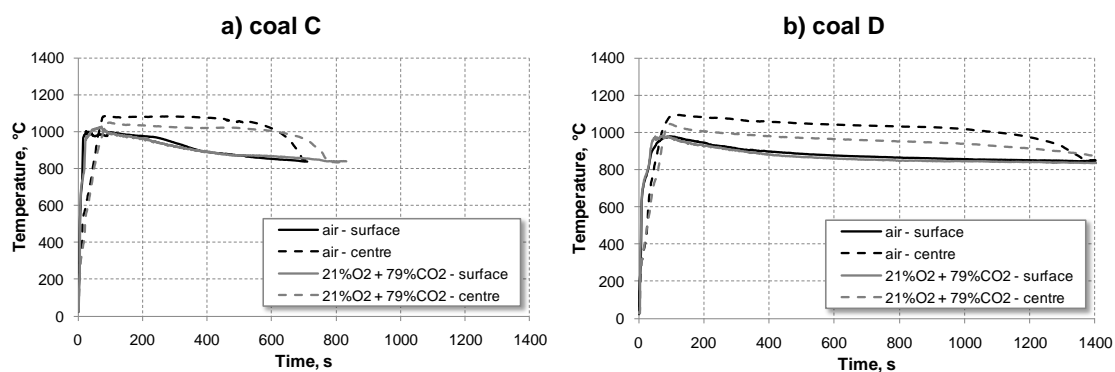


Fig. 3. Temperature profiles for coal C (a) and coal D (b) combusted in CFB in air and $21\%O_2+79\%CO_2$

As expected, the total combustion time, in both air and O_2/CO_2 mixture, for coal D was much longer (~90%) than that for more reactive coal C.

Figure 4 illustrates the effect of oxygen content in O_2/CO_2 mixtures on surface and centre temperatures measured for coals C and D. For both coals the trends are similar; these temperatures increase significantly with increasing O_2 concentration. In the case of coal D, the maximum difference between the centre and surface temperatures is larger than for coal C.

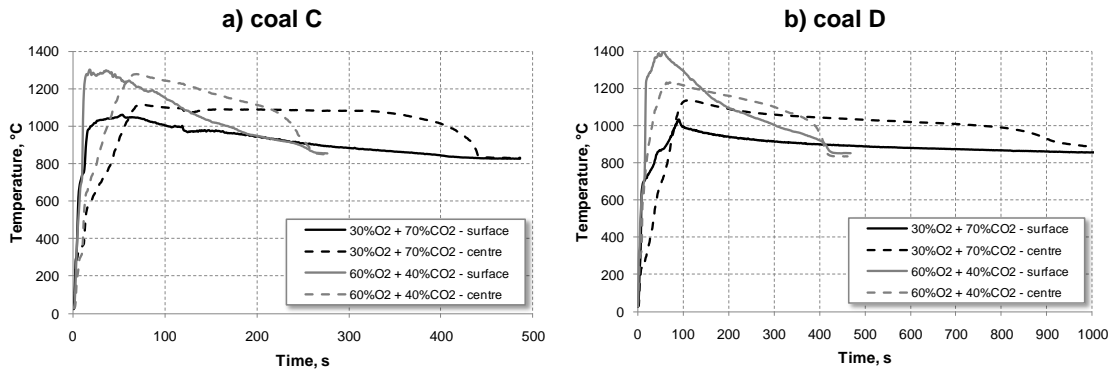


Fig. 4. Temperature profiles for coal C (a) and coal D (b) particles combusted in CFB in various mixtures of O_2/CO_2

Figure 5 shows the effect of gas composition on the ignition time of volatiles. Ignition time was characterized by the time required to achieve a visible flame. Larger heat capacity of CO_2 compared to that of N_2 retards the ignition of volatiles in O_2/CO_2 mixtures with 21% O_2 . However, when the concentration of oxygen in O_2/CO_2 mixtures is larger than 30%, the ignition time decreases with increasing O_2 content. The trends are consistent with those found in the literature, Toftegaard et al. (3) and Molina and Shaddix (8).

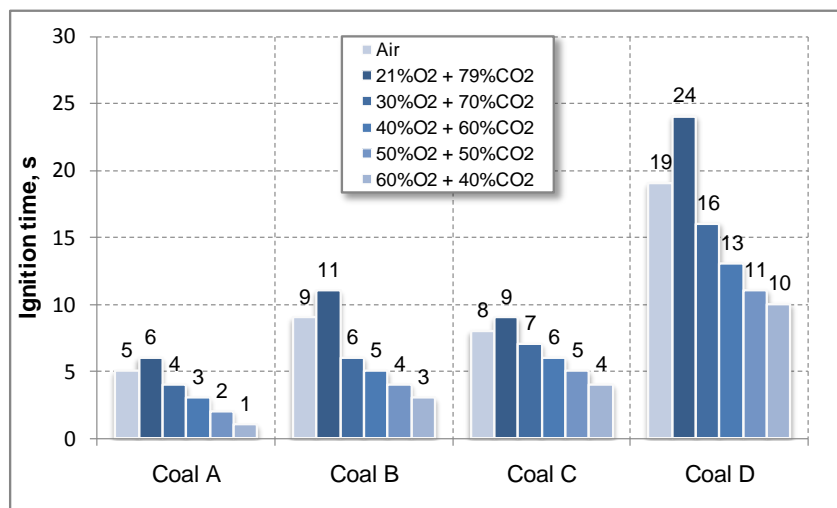


Fig. 5. Ignition time for bituminous coal particles combusted in various atmospheres

The influence of oxygen concentration in O_2/CO_2 mixtures on the devolatilization time is shown in Figure 6. Devolatilization time was the duration of the visible flame

(from ignition of volatile matter to the end of combustion of volatile matter). The devolatilization time decreases with increasing O_2 concentration for coals A, B and C and increases for coal D. Different devolatilization behaviour in the case of coal D can be associated with differences in its internal structure (porosity and pore size) and lower reactivity.

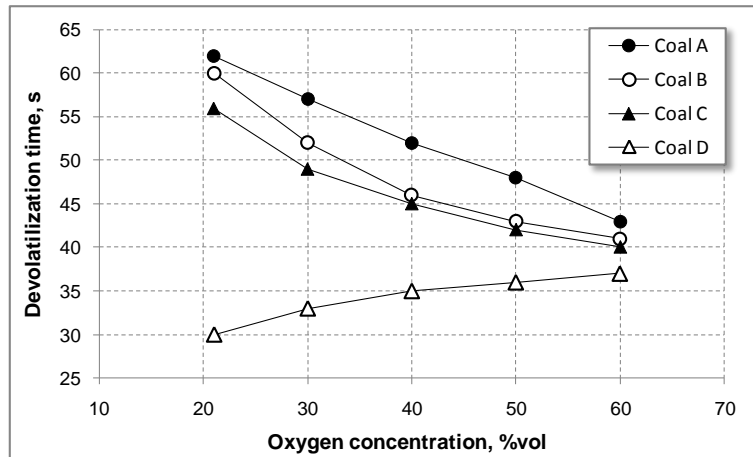


Fig. 6. Devolatilization time for coal particles combusted in mixtures of O_2/CO_2

Figure 7 shows the influence of O_2 concentration in O_2/CO_2 mixtures on the total combustion time. For all coals tested the total combustion time decreases with increasing oxygen concentration. The largest combustion times have been recorded for coal D. They are approximately 100% higher compared to those for coal C.

Figure 8 shows images of A coal particle at different stages of combustion.

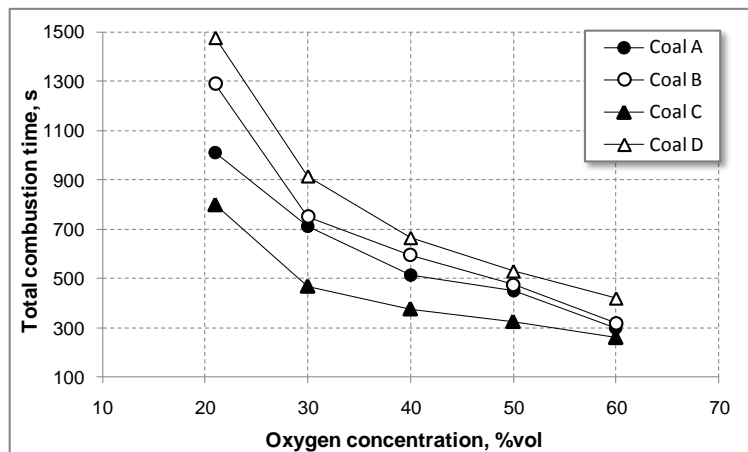


Fig. 7. Total combustion time for coal particles combusted in mixtures of O_2/CO_2

CONCLUSIONS

Oxy-fuel tests were conducted for 10-mm three Polish and one South African bituminous coal particles in a 12 kW bench-scale CFB combustor at temperature of $850^\circ C$. The experiments were carried out in air (base case) and mixtures of O_2/CO_2 with oxygen concentrations in the range from 21% to 60% vol. Results of proximate and petrographic analyses reveal that ash and inertinite (maceral that is less

reactive than vitrinite) contents in the South African are much higher than those in Polish coals. Therefore the combustion behaviour of these coals was different in air and O_2/CO_2 mixtures. Combustion in air proceeded at $\sim 50^\circ C$ higher centre temperatures and was slightly shorter in time compared to combustion in O_2/CO_2 mixture with 21% vol. O_2 . As expected, the total combustion time, in both air and O_2/CO_2 mixture, for South African coal was much longer ($\sim 90\%$) than that for more reactive Polish coal C. Larger heat capacity of CO_2 compared to that of N_2 also retards the ignition of volatiles in O_2/CO_2 mixtures with 21% O_2 . These trends are consistent with those found in the literature. However, when the concentration of oxygen in O_2/CO_2 mixtures is larger than 30%, the ignition time decreases with increasing O_2 content. Surface and centre temperatures increase significantly with increasing O_2 concentration. The devolatilization time decreases with increasing O_2 concentration for Polish coals A, B and C and increases for South African coal D. Different devolatilization behaviour in the case of coal D can be associated with differences in its internal structure (porosity and pore size) and lower reactivity. The total combustion time decreases with increasing oxygen concentration for all coals tested.

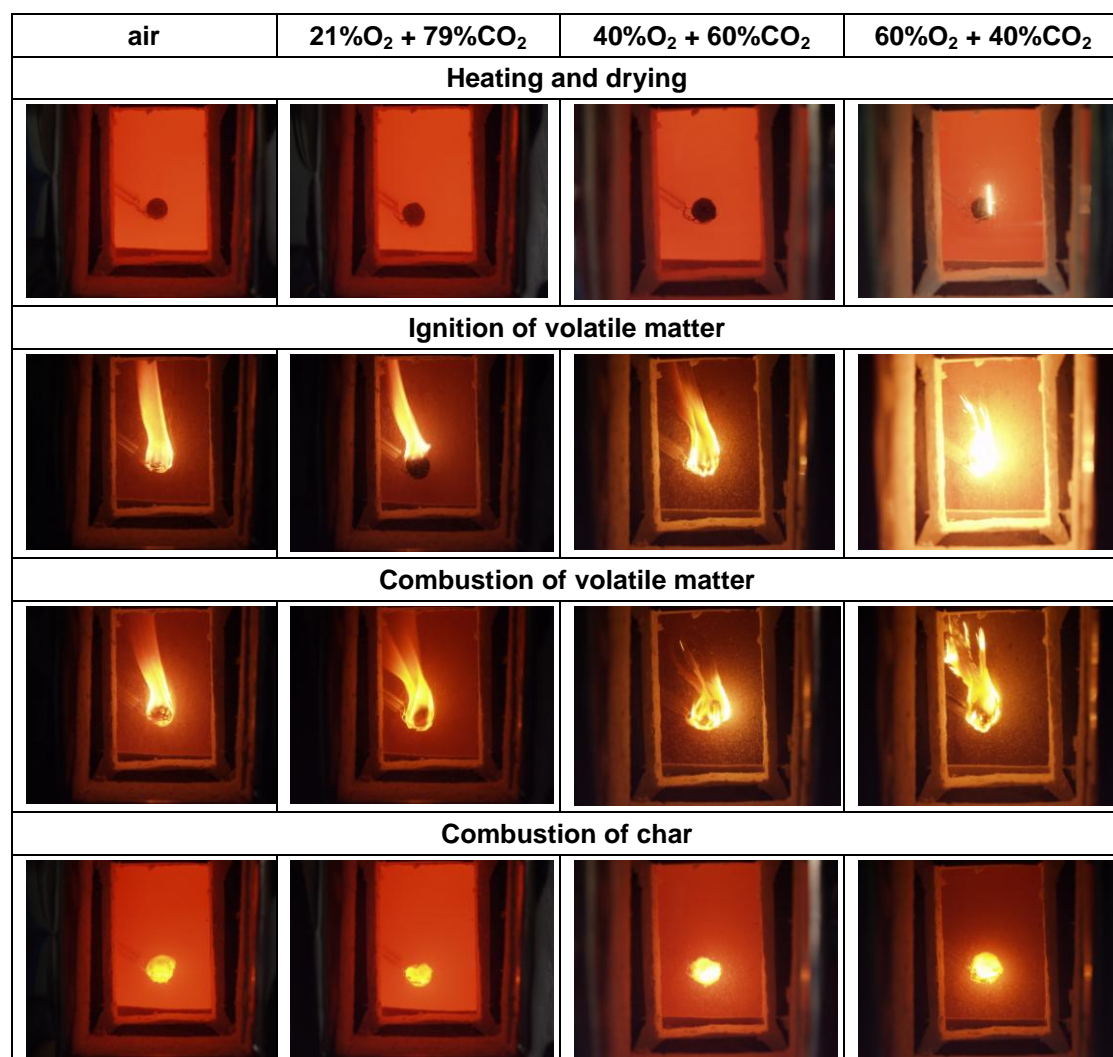


Fig. 8. Visualisation of A coal particle in CFBC in air and O_2/CO_2 mixtures

This paper included fundamental research and it is only the first step in studying and modeling of the oxy-fuel combustion process. The next step will be combustion of a portion of coal not only single coal particles. It will allow us to answer a question how a specific coal influences operation of oxy-CFB combustor like temperature profile in combustion chamber, real particles distribution of fluidized bed (fragmentation and erosion processes) and emission of pollutants. Next research will also answer a question how much oxygen in mixture of O₂/CO₂ is needed to have similar conditions like in the air combustion. Concentration of oxygen in O₂/CO₂ mixture will differ for various types of coal. It is very important for design and operation of oxy-fuel CFB units.

ACKNOWLEDGMENT

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NOTATION

- d_p – particle diameter, μm
 d_{50} – median particle diameter, μm
 ρ – density, kg/m^3

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