Comprehensive coal combustion characterisation under oxy-fuel conditions

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1. Introduction

Oxy-fuel combustion process, as one of the promising CO₂ capture technology, has been extensively investigated over last years, but still lacks of complete data for modelling and validation of combustion process in CO₂ and H₂O rich atmosphere.

Thus the aim of this study is to utilize the research potential of three parties (IEN, IFRF and ABO) in order to investigate the influence of oxy-fuel conditions on the fundamental combustion processes like devolatilisation, char oxidation, ignition phenomena and gasification, and to provide the information how the examined coals will behave under realistic oxy-fuel combustion conditions.

2. Experimental

The work has been divided into different laboratory experiments covering key aspects of the coal combustion under oxy-fuel conditions. It addressed the impact of the oxy-conditions and coal type on devolatilisation, char oxidation and burnout; ignition phenomena of dust cloud: autoignition temperature and stand-off distance; combustion behavior of single coal and char particles and finally gasification process of the single char particles. The following coals were selected and investigated: Sebuku, Pittsburgh no. 8 and South African.

2.1. Devolatilisation, char oxidation and burnout

Devolatilisation and char oxidation tests were performed in two laboratory stands installed at IEN and IFRF. The main objectives were to investigate the influence of the oxy-fuel combustion conditions on volatile matter
release and char residue oxidation in comparison to air conditions and to evaluate the experimental data and obtain the apparent kinetic parameters for modelling.

The first facility, presented in Fig. 1, consists of the two, silicon carbide, electrically heated drop-tubes, 1.5 and 6 m long and of 40 mm i.d. In the first one, used for devolatilisation tests, coal is fed from the top and collected by the vertical, movable probe, while in the second, used for char oxidation tests, char is fed through various horizontal ports, installed along the tube height, and samples are collected at the bottom of furnace.

![Fig. 1. IEN's drop-tubes.](image1)

![Fig. 2. Isothermal Plug Flow Reactor.](image2)

![Fig. 3. Dust cloud ignition stand.](image3)

The second facility, presented in Fig. 2, has a total length of 4.5 m, of which 4.0 m of operating length, and an internal diameter of 150 mm. On the top of the reactor, a natural gas-fired precombustor, which produces gases of the desired composition, is located. The drop-tube furnace is provided with several ports for flue gas temperature and composition measurement and pulverized solid fuel injection. Particle residence time is to be changed by varying the injection port and the position of the sampling probe at the bottom of the reactor.

Devolatilisation has been performed at 900, 1100 and 1300°C and a residence times between 25 and 250 ms. Then the char, produced at 1300°C and in 300 ms, was oxidized both under conventional and oxy-fuel conditions, with a residence time between 100 and 1000 ms, at the same temperatures as in devolatilisation tests and oxygen concentration of 3, 6 and 9 %vol.

An example of conversion level trend versus residence time and temperature is shown in Fig. 4, where conversion is compared at 900 and 1100°C for the South African coal under conventional and oxy-fuel combustion environments, while in Fig. 5 is presented the comparison between conventional and oxy-fuel devolatilisation of South African coal.

![Fig. 4. Char oxidation profiles for SA coal.](image4)

![Fig. 5. Devolatilisation of Sebuku coal.](image5)

The results show that the devolatilisation atmosphere influences the volatile matter release – at high temperatures and heating rates, the CO₂ presence increases weight loss. This subsequently causes higher volatile matter yield in CO₂ than in N₂ atmosphere. As the char oxidation process is concerned differences between char oxidation in N₂/O₂ and CO₂/O₂ become more visible at lower O₂ concentrations (3%vol.), where gasification reaction plays more significant role in char consumption.
2.2. Dust cloud ignition of pulverized coal under oxycombustion conditions

The ignition process and flame stability of a dust cloud of coal under oxy-fuel conditions was investigated. A cylindrical, 1.5m long, electrically heated drop-tube furnace, presented in Fig. 3, was used for this purpose. The temperature of walls of the reactor and the gas streams were electrically controlled during the experiments. The flame front was observed through a quartz glass window. The experiments were done at three reactor temperatures: 1173K, 1273K and 1373K. The influence of carbon dioxide as well as water vapour content on the flame stand-off distance were investigated. The autoignition temperatures for the selected gaseous compositions were also determined.

The results show that the oxygen concentration and the temperature of the reactor in all cases influence the flame stabilization and its stand-off distance. There is no significant influence of the water vapour content in the oxidizing mixture on the flame stand-off distance for all investigated coals. The visible impact can be seen for the Sebuku coal where at 1273K and 1373K higher water content led to smaller stand-off distance of the ignition point.

2.3. Investigation of single coal and char particles combustion

Combustion behaviour and internal particle temperature during combustion process of single coal and char samples were experimentally studied in 21 and 35 % oxygen concentration with nitrogen or carbon dioxide as diluent gas. Experiments were carried out in laboratory setup composed of electrically heated horizontal tube operated at 1223K with observation window for high speed video recording (1000 fps), presented in Fig. 6. The studies included the three above mentioned bituminous coals and the chars obtained from these coals. Single particles were prepared manually into cuboidal solids with an average particle size and weight of 2 mm and 4 mg respectively. Char particles were obtained in nitrogen, in the same research stand, right before the beginning of combustion experiments.

During particle devolatilisation (while char was prepared) and combustion (when the main experiments were carried out), particle internal temperature was measured with a thin (0.5mm) thermocouple. Signal from sensor was collected every 10ms, which allowed to determine exhaustive temperature-time history profile.

Single particle experiments provided direct information regarding phenomena that can be distinguished during particle combustion: for coal particle – ignition, volatile matter release, its homogeneous combustion and char combustion; for char particle – ignition and char combustion.

Results from experiments show that carbon dioxide presence in atmosphere influences dynamics of combustion process. Differences in oxycombustion process, in relation to air combustion, manifest themselves in lower particle temperatures as well as more difficult and long volatile release. Visual dissimilarities in the described processes are clearly revealed in video material recorded with high speed camera.

2.4. CO$_2$ and H$_2$O gasification of coal char in a single particle reactor

In this study, the influence of CO$_2$ on the char consumption rate has been investigated in a single particle reactor, presented in Fig. 7. The reactor consists of a quartz glass tube inserted to a ceramic furnace, which is electrically heated. Experiments of single particles of around 0.5 cm in diameter were performed with 76 % CO$_2$ and 24 % N$_2$ at 1273 K, 1373 K and 1423 K. Moreover, additional tests were performed with 34 % H$_2$O and 66 N$_2$.

Two char gasification reaction rates (with CO$_2$ and H$_2$O) were determined from the measured CO concentrations of the product gases in the reactor system. The results show that the char gasification rates are very slow at 1273 K, but significantly faster at 1373 K: at the latter temperature, char conversion took around 30 minutes with 76 % CO$_2$ in the gas. Moreover, the results show that the char reactivity with respect to H$_2$O was slightly higher than with respect to CO$_2$ at the investigated temperatures. Finally the results show that char consumption by CO$_2$ and H$_2$O must be considered at temperatures typical of pulverized coal combustion. Kinetic correlations suitable for CFD-modeling are derived.
3. Conclusions

A complete set of experiments of fundamental combustion processes has been conducted in five laboratory stands. On the basis of the results, the following conclusions on the comparison of the conventional and oxy-fuel combustion can be drawn:

- At high temperatures (>900 °C) and heating rates (>10⁴ K/s), comparable to full scale combustion conditions, differences between devolatilisation kinetics in N₂ and CO₂ are visible.
- Yield of the volatile matter evolved during the devolatilisation in CO₂ is up to ~10% higher than in N₂ and varies between coals.
- Differences between char oxidation in N₂/O₂ and CO₂/O₂ become more visible at lower O₂ concentrations (3%vol.), where gasification reaction plays more significant role in char consumption.
- There is no significant influence of the water vapour content in the oxidizing mixture on the flame stand-off distance in dust ignition for all investigated coals.
- CO₂ presence in atmosphere lowers particle temperatures as well as it gives a more difficult and longer volatile matter release.
- Char reactivity with respect to H₂O was slightly higher than with respect to CO₂ at the investigated temperatures.
- Char consumption by CO₂ and H₂O must be considered at temperatures typical of pulverized coal combustion.