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# Experimental studies of single particle combustion in air and different oxy-fuel atmospheres

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## HIGHLIGHTS

- Particle temperature during combustion was lower in $O_2/CO_2$ than in $O_2/N_2$ mixture.
- Greater temperature differences were observed for coal then for char particles.
- $CO_2$ hindered volatiles release and inhibited particle swelling during combustion.
- Presence of $H_2O$ in oxy-fuel atmosphere increased temperature of combusted particle.

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## ABSTRACT

In this work, direct observation of char and coal single particle combustion in different gases mixtures has been performed. Investigation focused on the influence of atmosphere composition on combustion process and especially on the comparison between combustion in air-like versus oxy-fuel dry and oxy-fuel wet conditions. For these tests, particles from Pittsburgh coal and South African Coal were prepared manually to cubical shape (approximately 2 mm and 4 mg). To investigate fuel type influence on oxy-fuel combustion, some tests were also conducted for Polish lignite coal from Turów mine. Experiments were carried out in a laboratory setup consisted of an electrically heated horizontal tube operated at 1223 K with observation windows for high speed video recording (1000 frames per second). During the experiments, particle internal temperature was measured to obtain comprehensive temperature–time history profile. Results revealed that particles burned at higher temperatures in high water vapour content mixtures than in dry $O_2/CO_2$ mixture. This behaviour was attributed to lower molar specific heat of water than of $CO_2$ and four times higher reaction rate for char–$H_2O$ gasification reaction than char–$CO_2$ reaction. Also visible dynamic of combustion process recorded with the high speed camera differs for experiments carried with water vapour addition.



## 1. Introduction

Oxy-fuel combustion is a technology introduced with aim to help reduce $CO_2$ emission, which is especially urgent in recent times when demand for coal is still growing. In Poland, where more than 90% of electricity is generated from coal, the oxy-fuel technology with possible option of boilers' retrofitting, seems to be an especially attractive variant for $CO_2$ mitigation. However, oxy-fuel technology is only at pilot-scale and the knowledge of combustion mechanisms in changed atmosphere can be still perceived as insufficient.

Exhaust gas from oxy-fuel combustion contains mostly $CO_2$ an $H_2O$. Part of produced flue gas must be recycled to maintain proper heat exchange and safe operation within the boiler. Whether the recycled stream is dried or contains a significant amount of water is the matter of later optimization of combustion process as well as technical and economic analysis. But lately an agree is emerging, that at least some amount of water in recycled flue gases is inevitable [1,2]. So far a lot of effort was undertaken to investigate the difference between air and dry oxy-fuel combustion [2,3]. But it should be remembered, that $H_2O$ as well as $CO_2$ can participate in char gasification reactions and from that point of view, possible interaction of $H_2O$ in oxy-fuel combustion process should be better understood.

Char gasification reactions can significantly compete with combustion reactions but only under specific conditions. Those are high temperature and/or low oxygen concentration in gas mixture. In comparison to $O_2$–char reaction, gasification either with $CO_2$ or

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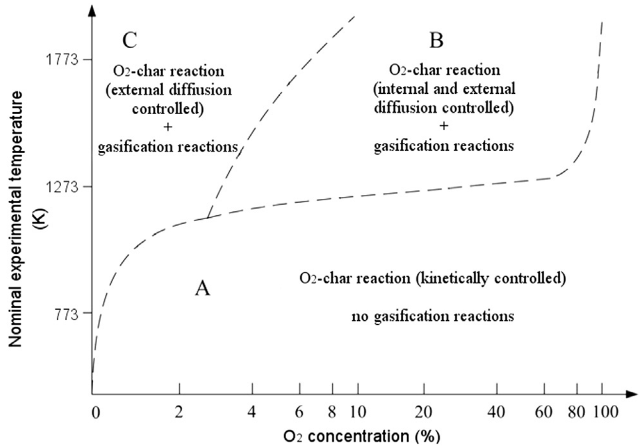


**Fig. 1.** Dominant reactions in char oxidation and gasification experiments (adapted from Chen et al. [3]).

$H_2O$ is much slower and requires a lot of external energy to take place. Thereby, if amount of oxygen molecules near char surface is sufficient, quick and exothermic combustion reaction is always promoted. On the other hand, when gas temperature is high enough, $O_2$—char oxidation is too quick for sufficient supply of oxygen molecules and reaction becomes limited by $O_2$ diffusion (both internal and external). In this case, gasification can be promoted, because char surface is still surrounded by plenty $CO_2$ and $H_2O$ molecules. Fig. 1 (adapted from Chen et al. [3]) presents the diagram that summarizes the conclusions from char oxidation and gasification experiments found in the literature. Diagram shows three temperature—$O_2$ concentration dependent regions, among which Regions B and C represent conditions in which gasification reactions are expected to noticeably contribute to char consumption, whereas in Region A only combustion reaction was found significant. Boundaries imposed on the regions are qualitative illustration only and are not conclusive, as emphasized by Chen et al. [3].

The questions that remain interesting are how and which gasification reaction influences char consumption more. While $CO_2$—char reaction was widely investigated in oxy-fuel combustion conditions, only a little effort was taken to study influence of variable steam concentration in oxy-atmosphere on parameters of combustion process [1].

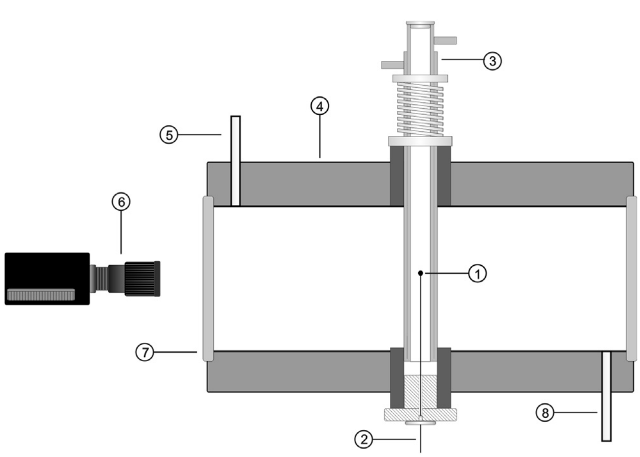


**Fig. 2.** Schematic diagram of Single Particle Combustion stand (SPC stand). 1. Coal/char particle, 2. Thermocouple, 3. Oil shield tube, 4. Reactor, 5. Gas inlet, 6. High speed camera, 7. Quartz window, 8. Gas outlet.

The aim of this work is to experimentally study and compare the behaviour of coal and char particles during high temperature combustion in 21 and 35% oxygen concentrations with different concentrations of $CO_2$, $H_2O$ and $N_2$, introduced as the diluent gases.

## 2. Experimental setup

### *2.1. Single particle combustion stand description*

Research stand for ignition and combustion of single particle allows carrying out experiments of quick fuel-particle combustion in controlled temperature and demanded gas mixtures. A schematic idea of Single Particle Combustion stand (SPC stand) is shown in Fig. 2. The main part of the rig is the reactor zone, which basically is a horizontal furnace, electrically heated up to 1000 °C (4), with observation windows at both ends. At the quarter of reactor length from quartz windows (7) are located two thermocouples used for heating control and setting of experimental temperature.

Tip of a 0.5 mm thermocouple (2) was inserted into the hole drilled in the coal particle (1) and with the thermocouple as a support, the particle was then inserted into the movable oil-cooled shield tube (3) inside the reactor zone. This tube, located at the vertical axis of furnace, created cool space inside the reactor and protected particle prior to the experiment's beginning. When demanded temperature conditions were stable, shield lock was released resulting in quick removal of the screen-tube from the reactor zone. Since that moment, investigated particle was exposed to the high temperature and oxidizing gases and this was considered the beginning of experiment. Ignition and combustion of fuel particle was recorded by high speed camera (6), Phantom v310 with applied recording speed of 1000 fps (frames per second). Camera was activated simultaneously with shield lock release.

Temperature of particle when placed into the cool shield tube before the experiment was about 110 °C. Thus when the shield blockade was released, experiment started with particle heating up.

Experiments were carried out with different gas mixtures ($O_2$, $N_2$, $CO_2$, $H_2O$, air), slightly above atmospheric pressure to prevent air leakage to the reactor zone. Gases from cylinders ($O_2$, $N_2$, $CO_2$, air) passed through an electric pre-heater (not shown) where water was vaporized and all gaseous components were mixed and preheated before entering the reactor (5). Water was supplied to the pre-heater by a peristaltic pump while gases flows were setup with flow meters. After passing the reactor zone (8), gas mixture reached a FTIR analyser which provided additional control of mixture composition.

### *2.2. Experimental conditions*

The experimental matrix is presented in Table 1. Basically, experiments were carried out for both coal and char particles in 950 °C with different atmosphere compositions (temperature was constrained due to capabilities of the heaters). Composed oxy-fuel atmosphere had different physical properties than air. Table 2 summarizes properties of gases used in this work, at experimental temperature. Gas mixture flow at reactor inlet was always 5 $dm^3$/min thus the laminar flow of gas did not disturb volatiles release and burning.

For such experimental conditions the average heating rate of particle was about 200 K/s. Although that slow heating rate is not comparable with industrial PC combustion ($10^4$–$10^6$ K/s), it allows to investigate sequential combustion of particle, which is essential for our studies.

From 3 to 5 coal or char particles were combusted for every experimental setup. For lignite coal tests were limited to one series and coal particles only. Totally, about 110 experiments were