Comparison of Flame Stability under Air and Oxy-Fuel Conditions for an Aerodynamically Stabilized Pulverized Coal Swirl Flame

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1 INTRODUCTION

Oxy-fuel combustion has been identified as a possible technology to implement carbon capture and storage (CCS) measures for pulverized fuel based combustion. The flue gas recirculation, which lays the base for oxy-fuel combustion processes, results in large quantities of carbon dioxide within the oxidiser stream. In comparison to conventional air supplied combustion, this "substitution" of nitrogen by carbon dioxide leads to significant differences, which are largely still subject of research. Among those is the flame stability for air and oxy-fuel flames of pulverized coal.

This work presents investigations on this topic conducted with the same equipment for both types of combustion to identify some underlying differences or commonalities for both types of combustion.

2 EXPERIMENTAL SETUP

2.1 Combustion chamber

The experiments presented have been conducted at the bench scale pulverized fuel combustion facility of the Institute of Heat and Mass Transfer at RWTH Aachen University. The principal component of this plant is an experimental furnace shown in Figure 1a. It consists of a top-fired cylindrical combustion chamber with an inner diameter of 400 mm and an overall length of 4200 mm. The burner port is vertically displaceable along the combustion chamber’s centerline; it can hold cylindrical burners up to diameters of 150 mm. Staging air can be provided through the annular gap between the cylindrical burner port and the wall of the combustion chamber offering the possibility to operate the investigated burners at different local air ratios (see also section 3). Four ports give access to the combustion chamber to apply different measurement techniques to the flame (see fig 1b). Two of these ports are equipped with special windows for visual inspection of the flame and application of optical
techniques; the two remaining ports are equipped to hold probes for investigations inside the combustion chamber. A flue gas quench is placed below the combustion chamber in order to cool down the flue gas before entering the stack; the quenching is done by means of water injection.

The composition of gas flows providing the oxygen required by the combustion can be varied. At first, air as conventional oxygen supply can be used to sustain combustion. Furthermore, a synthetic mixture of oxygen ($O_2$) and carbon dioxide ($CO_2$) can be used as oxidiser carrier in order to investigate the oxy-fuel combustion of pulverized fuels. Finally, there is also a rig to recirculate flue gas and enrich it with $O_2$ for investigations of realistic oxy-fuel conditions [1]. However, this rig has not been used for the presented experiments; these were conducted with synthetic mixtures only.

![Diagram of Experimental furnace](image)

(a) General cross section  
(b) Cross section through the observation ports

Figure 1: Experimental furnace (All dimensions in mm)
2.2 Burner

The swirl burner for the experiments presented has been specifically developed for oxy-fuel operation with low oxygen contents of the oxidiser streams. Among several other measures, establishing an intense backflow to the burner quarl proved to be very effective in order to provide a sufficient amount of heat for a fast and stable ignition \([1, 2]\). A stable oxy-fuel combustion of pulverized coal has been obtained with this burner for oxygen contents down to 18\%. A cross section through the burner quarl is shown in figure 2. The pulverized fuel is provided together with the primary oxidiser stream through the inner annulus. A major portion of the oxidiser flow through the burner is provided through the secondary annulus. This flow is swirled before entering the combustion chamber. A tertiary oxidiser flow is entering through the annular gap between the burner and the burner port. The flow field in the vicinity of the burner is predominantly governed by these gas streams; thus, these streams are embraced in the parameter \(\lambda_{\text{local}}\) (for definition and significance see section 3).

Furthermore, a staging stream is provided through the annular gap between the burner port and the combustion chamber’s wall (see figure 1a). The outer diameter of the burner stone is 360 mm resulting in a gap width of approx. 20 mm (depending on the slagging on the wall). The flow of all oxidiser streams can be adjusted separately for each stream by mass flow controllers installed in the oxidiser supply lines.

2.3 Measurement Techniques

The experimental facility is equipped with measurement systems to monitor continuously the operating state of the flame. In addition, several measurement techniques can be applied directly to the flame through the combustion chamber’s measurement ports (see Fig. 1). By positioning the displaceable burner port at several heights, measurement planes in different distances to the burner were realized.
2.3.1 Chemiluminescence imaging

To investigate the main reaction zone of homogenous combustion in the gas phase, which coincides with the zone of high radical activity [3], the spontaneous emission of UV radiation by excited OH radicals (denoted OH*) at 307 nm has been recorded. This radiation has been captured by a CCD camera system mounted in front of the measurement port no. 1 (see Fig. 1b). The camera has been equipped with an image intensifier in combination with an UV lens and a band pass interferential filter of 10 nm bandwidth centered at 307 nm. At each measurement position, 150 images were captured with an exposure time of 100 ms at a rate of 3 frames per second. These images were averaged in order to display the average chemiluminescence emissions. Several of these images taken at different positions from the burner were finally assembled to obtain a map of the entire flame (see figures 3, 5 and 7).

A background image has been taken for each measurement and subtracted from the averaged flame emission image in order to eliminate the influence of the combustion chamber’s hot internal wall. For this purpose, the flame has been shut down and an image was acquired immediately in order to reduce the effect of the cooling of the walls to the background image. The intensity values recorded with this technique were given in arbitrary units as measured by the CCD sensor. The main purpose of the chemiluminescence imaging is the investigation of flame structures, which concerns position and relative intensities of reaction zones; thus, absolute intensity values are of minor importance, and an elaborate calibration of the camera to absolute intensity values may not be conducted.

2.3.2 Laser Doppler Velocimetry

Velocity measurements inside the flame have been carried out using Laser Doppler Velocimetry (LDV). This technique – as implemented at the test facility – allows the determination of axial and tangential mean velocity components with high spatial resolution. For this purpose, two pairs of different colored laser beams are crossed to form a measurement volume. Due to the comparatively large working distance between the optics mounted outside of the combustion chamber, individual beam optics with single beam adjustment are used for laser transmission. To reduce the effort of beam alignment, a back scattering setup is realized having the transmission and the receiving optics mounted on the same rack. This rack is installed in front of observation port no. 1 (Fig. 1b) on a displaceable traverse in order to place the measurement volume at different radial positions.

An additional seeding of the flow with tracer particles within a coal flame is not necessary since the density of coal and ash particles is considered sufficiently high within the flame. The particle size gives rise to the assumption that the measured particle velocities represent the mean gas velocities [4]; turbulent fluctuations were not considered for this study.

2.3.3 Flue Gas Analytics

To analyse flue gas emissions and to assess stability and sufficiency of the investigated flame, a flue gas analyser system is installed at the stack subsequent to the quench (Fig. 1a). A small sample stream of flue gas is continously purged from the stack, dried in a refrigerant type dryer and fed into the analyser system. The CO content of the flue gas which serves as an indicator for a stable and sufficient combustion (low values indicate a stable combustion)
is measured by an NDIR (non-dispersive infrared) spectrography based analyser (ABB AO 2000 series). With this device, CO concentrations from 0 ppm to 3000 ppm can be detected.

### 3 Settings and Investigated Cases

#### 3.1 Parameters Varied

The main parameter to vary the flame characteristics of the burner presented in section 2.2 is the local oxygen ratio $\lambda_{\text{local}}$. In contrast to the overall oxygen ratio $\lambda$, which is defined in eq. 1 following the conventional definition of the air ratio, $\lambda_{\text{local}}$ takes only the amount of oxygen provided directly through the burner into account. It compasses the oxygen provided by the primary, secondary and tertiary stream (see figure 2).

$$
\lambda = \frac{\dot{m}_{O_2, \text{provided}}}{\dot{m}_{O_2, \text{required}}} = x_{O_2} \cdot \frac{M_{O_2}}{M_{\text{Oxydiser}}} \cdot \frac{\dot{m}_{\text{Oxydiser, provided}}}{\dot{m}_{O_2, \text{required}}}
$$

(1)

The amount of oxygen resulting from the difference between $\lambda_{\text{local}}$ and $\lambda$ is provided by a staging flow entering close to the walls of the combustion chamber (see figure 1a). This distinction is made due to the fact that the combustion flow field is mainly dominated by streams entering through the burner due to their higher momentum flows and their immediate inflow into the main combustion zone. In contrast, the staging flow enters at a zone where the progress of the combustion process is already advanced. The total oxygen ratio for all experiments was kept constant at 1.3, whereas the local oxygen ratio has been set to values of 0.6, 0.8 and 1.0.

In addition to variations of local oxygen ratio, different compositions of the oxidiser streams were applied: as reference case for comparison to conventional combustion, air has been used as oxidiser (denoted AIR). Two oxy-fuel cases with different oxygen contents $x_{O_2}$ have been investigated: a concentration of 21 vol $-\%$ O$_2$ (denoted OXY-21) to have a direct comparison between conventional air and oxy-fuel combustion with regards to the oxygen content, and a concentration of 25 vol $-\%$ O$_2$ (denoted OXY-25) delivering nearly identical momentum flows through the burner as for the air case. To illustrate this, the momentum flows – normalized for the air case with $\lambda_{\text{local}} = 1$ – are shown in Table 1.

<table>
<thead>
<tr>
<th>$\lambda_{\text{local}}$</th>
<th>AIR</th>
<th>OXY-21</th>
<th>OXY-25</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.000</td>
<td>1.438</td>
<td>1.003</td>
</tr>
<tr>
<td>0.8</td>
<td>0.640</td>
<td>0.920</td>
<td>0.642</td>
</tr>
<tr>
<td>0.6</td>
<td>0.360</td>
<td>0.518</td>
<td>0.361</td>
</tr>
</tbody>
</table>

#### 3.2 Parameters Kept Constant

Pre-dried and ground Rhenisch lignite was used as fuel; the ultimate analysis is given in table 2 as well as information on the particle size distribution. The thermal output has been kept at 60 kW$_{th}$ for all investigated flames resulting in a coal massflow of 9.5 kg/h.
Table 2: Properties of utilized fuel

(a) Ultimate analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>mass fraction as received</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>57.50%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>5.22%</td>
</tr>
<tr>
<td>Oxygen</td>
<td>18.98%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>0.55%</td>
</tr>
<tr>
<td>Sulfur</td>
<td>0.23%</td>
</tr>
<tr>
<td>Water</td>
<td>11.80%</td>
</tr>
<tr>
<td>Ash</td>
<td>5.72%</td>
</tr>
</tbody>
</table>

Lower heating value 22.63 MJ/kg

(b) Particle size distribution

<table>
<thead>
<tr>
<th>D10 (10 % below)</th>
<th>4 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50 (50 % below)</td>
<td>25 µm</td>
</tr>
<tr>
<td>D90 (90 % below)</td>
<td>124 µm</td>
</tr>
</tbody>
</table>

Furthermore, the total oxygen ratio \( \lambda \) (see eq. [1]) was kept constant at a value of 1.3. For the primary air, a flow rate of 8.5 m\(^3\)N/h was found from former experiments to guarantee a continuous transport of fuel into the combustion chamber; thus, this flow rate was also kept constant for all experiments. The flow rates for the remaining flows (secondary and tertiary streams) were calculated by subtracting the primary flow from the total oxidiser flow rate through the burner given by the particular \( \lambda_{\text{local}} \) and distributing the remaining flow rate to the secondary and the tertiary stream by fixed ratios. A portion of 0.15 of the total burner flow was fed to the tertiary stream, the remaining fraction of 0.85 was provided as secondary stream.

The swirl of the secondary stream is described by a swirl ratio \( SR = \frac{v_{\text{tan}}}{v_{\text{ax}}} \) with \( v_{\text{tan}} \) representing the tangential velocity and \( v_{\text{ax}} \) representing the axial velocity of the secondary stream at the annulus. A swirl rate of \( SR = 1 \) has been employed for this study.

4 Observations and Results

4.1 Global Judgement of Flame Stability

A stable combustion has been obtained for all three cases (AIR, OXY-21, OXY-25) for \( \lambda_{\text{local}} = 1.0 \) as well as for \( \lambda_{\text{local}} = 0.8 \). These flames were characterized by continuously low and stable CO concentrations in the single digit range. For a further reduced local oxygen ratio – and thus reduced flow through the burner, the results were different:

- For the AIR and OXY-25 cases with \( \lambda_{\text{local}} = 0.6 \), the CO measurement at the stack indicated a less stable and partially incomplete combustion: the CO concentration values were raising and leveling out in the range between 100 ppm and 200 ppm with sporadic peaks up to 3000 ppm. Furthermore, distinct fluctuations of the CO concentrations were observed, and strong overshoots occured frequently. However, a pure visual inspection by eye through an observation port did not deliver clear evidence of an instable flame (pulsating or extinction of the flame).

- For the OXY-21 case with \( \lambda_{\text{local}} = 0.6 \), a stable combustion is still observed characterized as described above by low and stable CO concentrations.
4.2 Changes of Flame Structure

The representations of the flame structures by chemiluminescence imaging and LDV measurements enlighten some reasons for different characteristics of the flames regarding the stability and sufficiency of combustion. Fig. 3 compares the three AIR cases: the difference between the two stable cases ($\lambda_{\text{local}} = 0.8$ and $1.0$) and the instable case ($\lambda_{\text{local}} = 0.6$) is clearly pronounced.

For a high local oxygen ratio of $\lambda_{\text{local}} = 1.0$, the main combustion zone is attached to the burner quarl and extends to an axial distance of approx. 200 mm. Furthermore, the zone of intense combustion close to the burner quarl seems to spread out into the border regions of the combustion chamber outside the frame of the measurement port and thus unobservable. All in all, this flame shows typical features of a swirl flame: a short and comparatively widespread flame in the very vicinity of the burner. These observations agree well with the original flame design concept for this burner ([1, 2]).

A reduced local oxygen rate of $\lambda_{\text{local}} = 0.8$ and thus, an increased flow for the staging stream, leads to a prolonged flame as one would expect. The highest intensities are still recorded close to the burner quarl (note that the maximum value is increased compared to the case of $\lambda_{\text{local}} = 1.0$), and the overall characteristics are similar to the $\lambda_{\text{local}} = 1.0$ case.

For the further reduced oxygen concentration of $\lambda_{\text{local}} = 0.6$, the flame characteristics change considerably: the flame length increases significantly caused by the increased amount of staging flow. Two streaks marking the edges of the swirl vortex can be recognized in the upper part of the combustion chamber in lieu of the main combustion zone attached to the burner quarl. In contrast to the two other cases, the vortex does not spread in extension of the conical burner quarl, but retains a nearly constant diameter.

These observations are backed by the measurements of the axial flow velocity as shown for $\lambda_{\text{local}} = 1.0$ in Fig. 4a and for $\lambda_{\text{local}} = 0.6$ in Fig. 4b: the $\lambda_{\text{local}} = 1.0$ case shows a for both measured velocity profiles a backflow zone at the combustion chamber axis with negative velocities (directed towards the burner) in which a recirculation of hot combustion products occurs (see also section 2.2). Furthermore, the spot of maximum velocity moves radially outwards induced by the conic burner quarl.

In comparison, the velocity profiles for the $\lambda_{\text{local}} = 0.6$ case reveal two significant differences: the velocity profile at 100 mm does not show a backflow zone, and the spot of the maximum axial velocity is closer to the centerline and not moving outwards as the distance to the burner is increased. This corresponds to the two streaks found from chemiluminescence imaging. These observations can be summed up as follows:

- The swirl vortex separates from the conic burner quarl and remains at a constant diameter in the center of the combustion chamber.

- The recirculation of hot flue gas products to the burner breaks down; the distinct backflow zone cannot be found.

For the OXY-25 cases – the comparison for these are shown in Fig. 5 – the flame structure changes in a way very similar to the AIR flame as already indicated by the flue gas emission measurements. In general, the chemiluminescence intensities are lower, which might be attributed to the reduced temperatures for oxy-fuel combustion. Furthermore, the prolongation of the flame from $\lambda_{\text{local}} = 1.0$ to $\lambda_{\text{local}} = 0.8$ is not as pronounced as for the AIR case. But as
the AIR case, these two OXY-25 cases with the high values for $\lambda_{\text{local}}$ are characterized by a main combustion zone in the vicinity of the burner quarl. Its increased size is probably caused by reduced net reaction rates due to reduced temperatures and increased CO$_2$ concentrations.

The $\lambda_{\text{local}} = 0.6$ case exhibits flame structures very similar to the respective AIR case: streaks indicating the edge of the now inbending vortex and a distinctively prolonged reaction
Figure 5: Chemiluminescence intensities for the OXY-25 cases (arbitrary units)

Figure 6: Mean axial velocities for OXY-25 at two different distances $x$ from the burner zone. As for the air case, a partition of the combustion zone into two parts can be recognized which might be caused by the entrance of the staging oxidiser flow into the central combustion zone. The LDV velocity measurements show features similar to the AIR flames, too (Figures 6a and 6b): an inward bending of the maximum velocity spot as well as a breakdown of the recirculation zone are observed.
Figure 7: Chemiluminescence intensities for the OXY-21 cases (arbitrary units)

Figure 8: Mean axial velocities for OXY-21 at two different distances $x$ from the burner

In contrast to the two cases considered so far, the investigated OXY-21 cases show a considerably different behaviour of the characteristic flame (see Fig. 7) structures as already suggested by the global CO emission measurements. First of all, a distinctively lifted flame occurs for all investigated cases: the main reaction zone is further remote from the burner quarl than in the AIR and the OXY-25 cases. Furthermore, the intensities of the OH* emissions are further reduced following the trend already noted for the OXY-25 cases. How-
ever, the transitions of the flame pattern characteristic observed for the two other cases with \( \lambda_{\text{local}} = 0.6 \) does not occur: the flame is lifted, but still possesses a compact reaction zone in the vicinity of the burner. No clues to a separation and inward bending of the swirl vortex were found.

The LDV velocity measurements support these observations (see Fig. 8a and 8b): in fact, the intensity of the backflow towards the burner is reduced as the local oxygen ratio \( \lambda_{\text{local}} \) is decreasing, but a breakdown of the recirculation as observed for the two other cases did not occur here. Also the conical displacement of the velocity maximum observed for the cases with increased local oxygen ratios can be recognized for this case. All in all, the OXY-21 case with \( \lambda_{\text{local}} = 0.6 \) just carries forward the trends found for the cases with higher local oxygen ratios.

### 4.3 Interpretation

The main reason for the different behaviour of the flame and the transition to a different flame pattern at low local oxygen ratios at the burner can probably be found from the different momentum flows through the burner for the different cases. Table 1 lists the normalized momentum flows for the investigated cases. The differences between the considered cases arise from the following two effects:

- When passing over from air to oxy-fuel combustion and replacing \( \text{N}_2 \) by \( \text{CO}_2 \), the increased molar weight of \( \text{CO}_2 \) yields an increased momentum flow when applying same oxygen concentrations. By comparing the numbers for the AIR and the OXY-21 cases, this effect can be identified.

- By changing the oxygen concentration without changing the oxygen ratio \( \lambda \), the total mass flows are reduced. This effect can be identified from eq. [1], by increasing the oxygen concentration \( x_{\text{O}_2} \), the mass flow \( \dot{m}_{\text{Oxydizer}} \), provided of the oxidiser must be reduced in order to obtain the same oxygen ratio \( \lambda \) for the same fuel mass flow. This effect accounts for the differences between the two oxy cases OXY-21 and OXY-25.

The two described effects may also counterbalance each other. This is the reason for the nearly identical momentum flows of the AIR and the OXY-25 cases: the increase caused by the higher molar weight of \( \text{CO}_2 \) is equalized by the reduced overall flow caused by the increased oxygen concentration.

Recapitulating the observation of the flame characteristics and the emission measurements presented in sections 4.1 and 4.2, one might assume that the reason for the observed similarities or differences of the flame characteristics and stability can be ascribed to the different momentum flows. The OXY-21 flames have significantly higher momentum flows through the burner; thus, the near burner flow field features are supported by these increased momentum flows even for low local oxygen ratios (and thus oxidiser flows), whereas the reduced - and nearly identical - momentum flows for the two other cases cannot sustain the flow characteristics and thus cause the separation of the swirl vortex and the breakdown of the recirculation zone. Concluding these thoughts, the transition to the different flame patterns can mainly be ascribed to aerodynamic effects globally governed by the momentum flows through the burner.
5 CONCLUSION

The stability behaviour and the characteristics have been investigated for oxy-fuel flames (21 vol − % and 25 vol − % O₂) as well as for air flames. Essentially, the local oxygen ratio \( \lambda_{\text{local}} \) served as the main variable parameter besides the composition of the oxidiser stream. The investigations were conducted using global emission analytics to measure the concentration of CO within the flue gas, OH* chemiluminescence imaging to map the reaction zones of homogenous combustion and Laser-Doppler-Velocimetry to measure the mean flow velocities inside the flame.

A similar behaviour regarding the stability and sufficiency of combustion was found for flames with similar momentum flows through the burner: the flame characteristics of the OXY-25 flames were found to be very similar to those of the AIR flames. For low local oxygen ratios, a separation of the swirled vortex from the conical burner quarl and a breakdown of the central recirculation zone leading hot combustion products to the burner were observed. The OXY-21 flames do not show this alteration of flame shape: the increased momentum flow due to the higher molar weight of CO₂ counteracts the separation of the flow from the burner quarl. This leads to the assumption that the behaviour and the shape of the investigated flames are mainly governed by aerodynamic effects.

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References


