

# Techniques for in-flame measurements

International Flame Research Foundation

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UNIVERSITY OF TWENTE.

**RelCom**<sub>2</sub>  
Reliable Combustion

 **IFRF**

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## International Flame Research Foundation

### Internship report

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Period:  
01/09/2015 - 30/11/2015

Report submitted to

**UNIVERSITY OF TWENTE.**

Faculty of engineering technology  
department of thermal engineering

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## I. Preface

Before you lies my internship report on techniques for in-flame measurements. I was engaged in writing this report from September to December 2015. As a master student in mechanical engineering, part of my curriculum is to undertake an internship. The internship was undertaken at the International Flame Research Foundation(IFRF) located in Livorno, Italy. IFRF is the research and networking hub of the global combustion and energy community. It performs research, facilitates access to research capabilities and expertise worldwide, and disseminate information. The mission is to advance applied combustion research and to promote cooperation and information transfer throughout the international combustion and energy arena.

I would like to thank my supervisors and colleges, Giovanni Coraggio, Marco Faleni and Cristiana Gheorge for their guidance and support during this internship. I also wish to thank Arthur Pozarlik for his help in finding the internship.

*Hans Geerligs, Livorno, 27-11-2015*

## II. Summary

The large quantity of CO<sub>2</sub> emitted into the atmosphere each year leads to the greatest overall contribution to the greenhouse effect of any pollutant. The combustion of pulverized coal in conventional utility boilers is believed to contribute about 10% to the enhanced greenhouse effect. Fossil fuel fired power stations are targeted for application of CO<sub>2</sub> removal technologies because they represent easily identifiable point sources. A solution is separation of the CO<sub>2</sub> from the flue gas and non-atmospheric disposal. Because air is used as the comburent, the post-combustion gas contains approximately 15% CO<sub>2</sub>. The low CO<sub>2</sub> concentration, due to the high N<sub>2</sub> concentration, makes CO<sub>2</sub> separations techniques very energy-intensive and expensive. The process of separating and recovering the CO<sub>2</sub> can be simplified if the flue gas CO<sub>2</sub> concentration is maximized by minimizing the N<sub>2</sub> concentration. To increase the CO<sub>2</sub> concentration, oxy fuel technology is introduced. The combustion air is replaced by a mixture of O<sub>2</sub> and recycled flue gas (RFG). The RFG is required to control the combustion temperature. Theoretically this could lead to a post-combustion gas with a CO<sub>2</sub> concentration in the order of 95%. [5]

The RELCOM project (Reliable and Efficient Combustion of Oxygen/Coal/Recycled Flue Gas Mixtures) under the Seventh Framework Programme of the European Commission aims to further develop the oxy-fuel technology. It undertakes a series of applied research, development and demonstration activities involving both experimental studies and combustion modelling work to resolve existing technical uncertainties and barriers which inhibit commercial deployment of the technology. The project commenced in November 2011 and has a duration of 4 years. Tasks undertaken within the project include:

- CFD simulation to develop improved burner designs, flame stability assessment and scaling rules.
- Pilot-scale burner trials for assessment of novel burner designs and development of combustion monitoring and control systems.
- Medium-scale burner testing using pilot scale results and scaling criteria developed within the project.

The next step is to perform large scale experiments at the 20MWth CIUDEN facility. IFRF is assigned to take in-flame measurements. The objective is to provide information on the performance of the newly designed burners in different modes of operation. First a measurement plan is made where it is decided which measurements are taken. To analyse in flame conditions measurement probes are inserted through ports in the boiler wall. Measurements are taken at different insertion depths to map the conditions in the boiler. The boiler has numerous insertion ports spread over 5 different floors. This way measurements can be taken at all stages in the boiler. Most important for the burner characterization are measurements from port 6 and 7 in front of burner 2. Measurements are taken of three different operating modes:

- Baseline air mode (test code: S2-A1)  
The air mode is used for comparison. One of the key considerations in the project is the retrofitting of existing pulverized coal fired boilers. To achieve this, oxy-coal firing modes are designed to achieve similar characteristics to air combustion. Therefore it is important to compare all results to air mode.
- "conventional" oxy combustion (test code: S2-O1)  
The conventional oxy mode is based on previous large scale tests. In these tests the ideal recycle ratio has been determined. Oxygen injection is divided equally to the different input flows of the burner.
- New concept oxy combustion (test code: S2-O17)  
The new concept of oxy combustion modifies the oxygen concentrations in the different inlet streams of the burners. The goal is to improve flame stability, combustion efficiency and emission production. Because of confidentiality the concentrations are not presented in this report.

Measurements are taken for temperature, heat fluxes and chemical species inside the furnace. During the campaign some difficulties occurred with the carbon dioxide and sulphur dioxide measurements. Error estimations have been computed and provided with the data. The data is presented in a report and shared with all the members of the project. In the report the raw data is delivered with interpretation of the in-flame conditions and accuracy of the data. The obtained measurement data is used to validate CFD simulations, flame stability assessments and scaling rules. This report focusses on the characterisation of the boiler and the different settings. Validation of the simulations is out of the scope of this report.

Using the measurement results the flames in the different settings are characterised. The conventional oxy mode showed a flame positioned farther away from the burner than the other settings. The effect of multiple burners in the boiler is also visible in the results. Measurements are not symmetric around the burner axis. In general the reaction speed seems higher to the middle of the boiler, which is between two burners. This could be caused by higher temperatures and better mixing. Carbon dioxide concentrations have been found to be around 80% in the flue gas. Unfortunately the measured values are not very accurate because of instrument malfunction. However the goal of reaching high carbon dioxide concentrations in the flue gas is reached. Using oxy fuel combustion, the flue gas is more suitable for processes like carbon capture. This provides a good base for future implementation of the technology.

Next to the species concentration, also normalized values for the emissions are calculated. The values are compared to average European data from PE International. The results for air case showed the experiment produced large quantities of nitrogen oxides and sulphur dioxides. This is mostly explained by the fact the facility was not operating NO<sub>x</sub> and/or SO<sub>2</sub> reducing instruments during the experimental campaign. Comparing the oxy mode to air, the drop in NO<sub>x</sub> production is most clear. Because the oxy fuel technology does not use ambient air, with high nitrogen content, nitrogen oxide production is drastically lowered.

The project has had a good result, it has been verified oxy-coal combustion is possible on a large scale. This means it can be implemented into real operating power plants within a reasonable time. Implementations of the technology will be an important step in reducing worldwide CO<sub>2</sub> emissions for the coming years. Now it is proven to be technically feasible the next step is to make it economically interesting for energy companies to implement the technology.

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# Chapter 1

## Introduction

The large quantity of CO<sub>2</sub> emitted into the atmosphere each year leads to the greatest overall contribution to the greenhouse effect of any pollutant. The combustion of pulverized coal in conventional utility boilers is believed to contribute about 10% to the enhanced greenhouse effect. Fossil fuel fired power stations are targeted for application of CO<sub>2</sub> removal technologies because they represent easily identifiable point sources. A solution is separation of the CO<sub>2</sub> from the flue gas and non-atmospheric disposal. Because air is used as the comburent, the post-combustion gas contains approximately 15% CO<sub>2</sub>. The low CO<sub>2</sub> concentration, due to the high N<sub>2</sub> concentration, makes CO<sub>2</sub> separations techniques very energy-intensive and expensive. The process of separating and recovering the CO<sub>2</sub> can be simplified if the flue gas CO<sub>2</sub> concentration is maximized by minimizing the N<sub>2</sub> concentration. To increase the CO<sub>2</sub> concentration, oxy fuel technology is introduced. The combustion air is replaced by a mixture of O<sub>2</sub> and recycled flue gas (RFG). The RFG is required to control the combustion temperature. Theoretically this could lead to a post-combustion gas with a CO<sub>2</sub> concentration in the order of 95%. [5]

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(a) Boiler port in front of a burner.

(b) Inserting the sampling probe.

**Figure 1.1:** Handling of the sampling probe.

Measurements are taken of three different operating modes:

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This report outlines the measurement campaign performed by IFRF. Particularly it focusses on the chemical composition measurements, for temperature measurements the reader is referred to the report by W.Broenink [4]. The report starts by describing the experimental setup. The data processing and inaccuracies in the results are discussed in chapter 3. In the next chapter the measurement results are presented and compared. In the final conclusion it is attempted to answer the main questions. The different firing modes are characterized including the produced emissions to determine the influence of the different operating parameters. Special attention is to the increase of CO<sub>2</sub> content for separation processes.

## Chapter 2

# Experimental setup

This chapter first gives a short description of the experimental facility where the measurement campaign is undertaken. Then all of the equipment used by IFRF is discussed in detail.

### 2.1. CIUDEN

The measurements are taken at the technology development centre for CO<sub>2</sub> capture of CIUDEN. An aerial photo of the facility is on the cover of this report. The facility is located in Cubillos del Sill (NW Spain). The main objective of the Technology Development Center (later, es.CO2), is the development and integration of the coal oxy-combustion, flue gas cleaning and CO<sub>2</sub> capture processes, as a necessary preliminary step before its application at commercial scale; in this sense, the sizing of the units that form the test facility have been carefully calculated to have results and data reliable to support the scale-up and to assure greater success of the industrial implementation.

A pulverised coal boiler with a capacity of 20 MWth is the core subject of the measurement campaign. The boiler incorporates four horizontal burners, each with a thermal capacity of 5 MWth. They are located on the opposite walls of the furnace, two on each side facing each other (wall firing). The burners are low NO<sub>x</sub> type burners and are dimensioned to lead the adjusted flows of oxidant in three main streams: primary, secondary and overfire comburents. Coal is conveyed by primary comburent flow through the pulverized coal ducts to the burners. The burners have the capability to modify the fluid dynamic characteristics (swirl type) of the secondary stream in order to allow the study of different flame configurations. Burners are equipped with natural gas ignitors for the boiler starting-up. Heat exchangers are inside the boiler to simulate realistic heat extraction from the gas. A flue gas cleaning line is attached to the boiler outlet. After the flue gas cleaning the flow is partly recycled back into the boiler, the remainder is send to the chimney. [6]

### 2.2. Probes

To measure flame characteristics, measurements inside the boiler are taken. The used probes are specifically designed for this purpose. The measurement instruments are inside long tubes which are inserted into the boiler at varying depths. The probes need a constant flow of cooling water to suppress high temperature levels. Thermocouples are used to measure temperatures because of their capability to operate reliable at high temperatures. For the experimental campaign four different probes are used. Each probe has an unique setup for measuring specific characteristics. The four probes are:

- Suction pyrometer, measures gas temperatures.
- Ellipsoidal radiometer, measures the radiation falling on an element of a plane surface.
- Total heat flux probe, measures the total heat flux absorbed by its receiving surface.
- Sampling probe, extracts a representative gas specimen for measuring species concentrations.

This report focusses on the analysing of the species inside the furnace, therefore the sample probe and gas analysing equipment is explained in the following sections. For more information about the other probes the report of Willem Broenink is referred to [4].

### 2.2.1 Sampling probe

To perform chemical gas concentration measurements inside the flame IFRF uses a sampling probe as schematically depicted in figure 2.1.

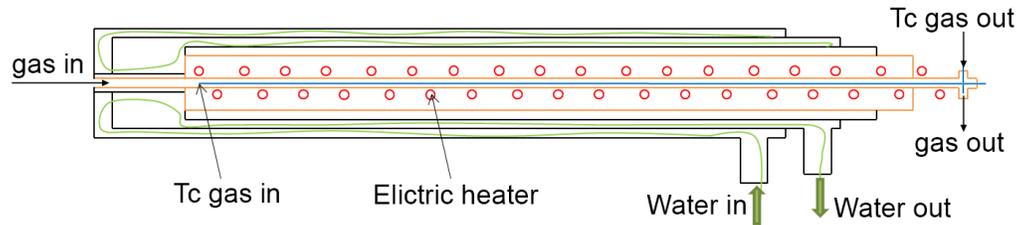
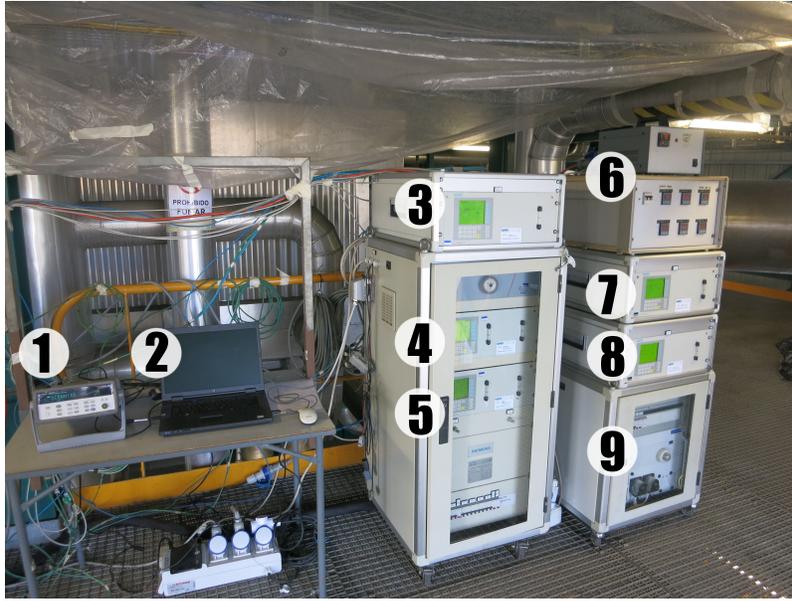


Figure 2.1: Scheme of the sampling probe.

The aim of the probe is to guarantee that the gas brought to the analyser is representative of the gas inside the flame. The flow entering the probe is still in a state of rapid evolution at elevated temperatures. This means the species concentrations will change over time because of the different reaction types: cracking of gas and fuel oil, pyrolysis, combustion reactions, dissociation and re-association. To conserve the initial species with original concentrations it is necessary to implement a so called conditioning process. Which means that the samples are cooled at a fixed cooling rate to a final temperature where the species will no longer evolve (or very little). To achieve such result the probe was designed with a short inlet tube cooled with water to quench the gases and to stop the reaction. The cooling rate is in the order of  $3e-3$  seconds. After this quick cooling the gases are electrically heated to keep the temperature in the range 180-250 °C to avoid condensation before the gas analysers. A thermocouple is placed after the conditioning and at the gas outlet, shown in figure 2.1. [3]

From the sampling probe the gas flow goes through a heated line to the filter. The filter removes solid particles from the sample to avoid disturbing the gas analysing and clogging of the lines by deposition of ash. After the filter the sample line reaches the suction pump with a dryer, removing water from the gas flow. The dryer operates at 3°C, cooling the sample down and condensing the liquid. From the dryer the sample goes to gas analysers. The analysers need dry gas, which explains the need for a dryer. The results are monitored in real-time from the connected laptop and can be used to verify a steady measuring situation. This information is used to commence the acquisition of the measurements.

The species detected by the analysers are:  $O_2$ ,  $CO_2$ ,  $CO$ ,  $NO_x$  and  $SO_2$ . The  $O_2$  analyser is a Siemens series 6 paramagnetic detector, the  $CO_2$ ,  $CO$ ,  $NO_x$  and  $SO_2$  are Siemens series 6 NDIR detectors calibrated in different ranges. Additional  $O_2$ ,  $CO_2$  and  $CO$  analysers are used to measure at high concentrations. In figure 2.2 all of the instruments are displayed, their description and calibration ranges are in the complementary table.



**Figure 2.2:** *Instrumental setup at CIUDEN.*

1. Agilent Data acquisition switch unit.  
All thermocouples and gas analysers are connected to the datalogger. The datalogger reads the signals every 2 seconds and sends it to the laptop.
2. Laptop.  
Uses Benchlink datalogger software to visualize received data realtime and directly saves all data.
3. Siemens Ultramat CO analyser, range 0-7.5 %
4. Siemens Ultramat CO analyser, range 0-800 ppm.  
Siemens Ultramat NO analyser, range 0-1000 ppm.  
Siemens Ultramat SO<sub>2</sub> analyser, range 0-1900 ppm.
5. Siemens Ultramat CO<sub>2</sub> analyser, range 0-30 %  
Siemens Oxymat O<sub>2</sub> analyser, range 0-25%.
6. Temperature regulators  
Adjust the gas temperatures inside the probe, in the flexible tube from the probe to the hot filter and in the flexible tube from the hot filter to the analysers.
7. Siemens Ultramat CO<sub>2</sub> analyser, range 0-100 %
8. Siemens Oxymat O<sub>2</sub> analyser, range 0-100%.
9. Suction pump including a dryer.

As the gas analysers are an important part of the measurement campaign, their principle of operation is explained in the following sections.

### 2.3. Siemens gas analysers

The Siemens gas analysers consists of the Ultramat 6 system for measurements of CO, CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub>. For measuring oxygen concentration the Oxymat 6 system is used.

#### Ultramat 6

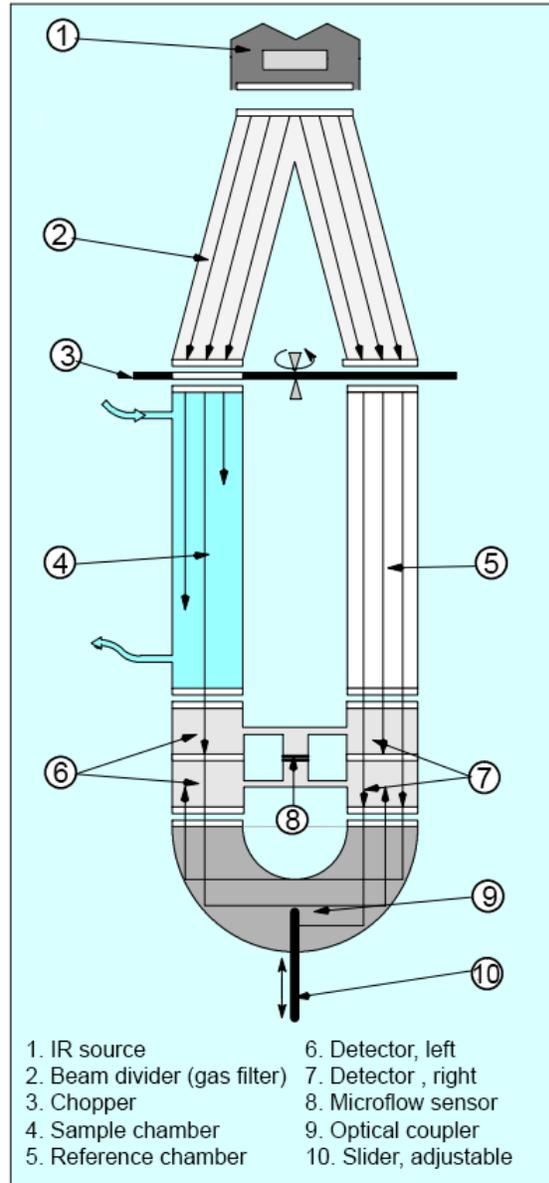
The Ultramat gas analyser operates according to the NDIR two-beam alternating light principle. The measuring principle is based on the molecule-specific absorption bands of infra-red radiation. The absorbed wavelengths are characteristic to the individual gases, but may partially overlap. This results in cross-sensitivities which should be reduced to a minimum.

Figure 2.3 shows the measuring principle. An IR source (1) which is heated to approximately 700 °C is divided by the beam divider (2) into two equal beams (sample and reference beams). The beam divider also acts as a filter cell.

The reference beam passes through a reference cell (5) filled with N<sub>2</sub> (a non-infrared-active gas) and reaches the right-hand side of the detector (7) practically unattenuated. The sample beam passes through the sample cell (4) through which the sample gas flows and reaches the left-hand side of the detector (6) attenuated to a lesser or greater extent depending on the concentration of the sample gas. The residual radiation is then absorbed by the detector cells filled with a defined concentration of the gas component to be measured. The detector cell heats up by the radiation, increases in pressure and causes a displacement measured by the microflow sensor.

Only the wavelengths absorbed by the component to be analysed are taken into account by the receiving cell which is filled with the same gas. If the mixture introduced into the measurement cell contains other species whose absorption band interfere with those of the gas being analysed, cross-sensitivity is possible. In this case it is necessary to filter the radiation emitted by the source by placing the parasitic gases in the filter cell; that is, by holding back the radiation emitted in the common wavelength bands. Compensation of this kind is not possible for particles (grey bodies which absorb all wavelengths) or for water vapour (condensation, complex spectrum), so that the gases must be carefully dried and freed from dust before introducing into the analyser.

The detector is designed as a double-layer detector. The center of the spectrum absorption band is preferentially absorbed in the upper detector layer, the edges of the band are absorbed to approximately the same extent in the upper and lower layers. The upper and lower detector layers are connected together via the microflow sensor (8). This coupling means that the spectral sensitivity has a very narrow band.



**Figure 2.3:** Working principle NDIR [7].

The optical coupler (9) lengthens the lower detector chamber layer optically. The infrared absorption in the second detector layer is varied by changing the slider position (10). It is thus possible to individually minimize the influence of interfering components.

A chopper (3) rotates between the beam divider and the sample cell and interrupts the two beams alternately and periodically. If absorption takes place in the sample cell, a pulsating current is generating which is converted by the microflow sensor (8) into an electric signal.

## Oxymat 6

In contrast to almost all other gases, oxygen is paramagnetic. This property is used as the measuring principle by the OXYMAT channel.

Oxygen molecules in an inhomogeneous magnetic field are drawn in the direction of increased field strength due to their paramagnetism. When two gases with different oxygen concentrations meet in a magnetic field, a pressure difference is produced between them.

One of the gases (1, Figure 2.4) is a reference gas (N<sub>2</sub>, O<sub>2</sub> or air), the other is the sample gas (5, Figure 2.4). The reference gas is introduced into the sample chamber (6) through two channels (4). One of these reference gas streams meets the sample gas within the area of a magnetic field (7). Because the two channels are connected, the pressure, which is proportional to the oxygen concentration, causes a flow. This flow is converted into an electric signal by a microflow sensor (3).

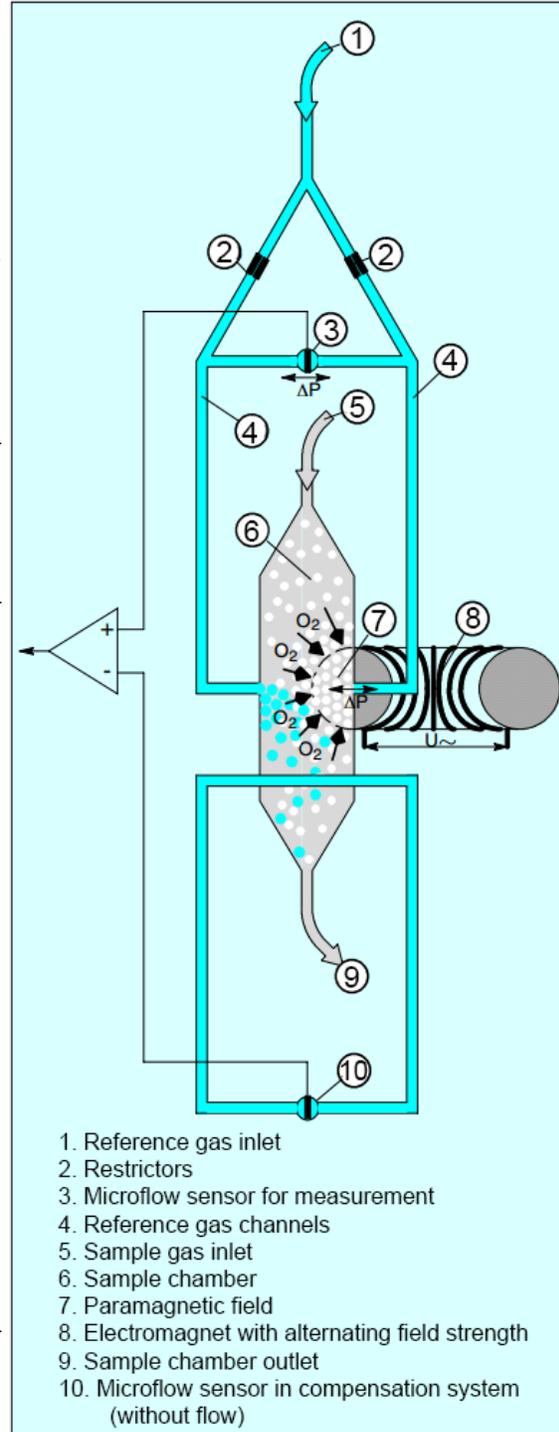
The microflow sensor consists of two nickel grids heated to approx. 120 °C which form a Wheatstone bridge together with two supplementary resistors. The pulsating flow results in a change in the resistance of the Ni grids. This results in a bridge offset which depends on the oxygen concentration in the sample gas.

Because the microflow sensor is located in the reference gas stream, the measurement is not influenced by the thermal conductivity, the specific heat or the internal friction of the sample gas. This also provides a high degree of corrosion resistance because the flow sensor is not exposed to the direct influence of the sample gas.

By using a magnetic field with alternating strength (8), the effect of the background flow in the microflow sensor is not detected, and the measurement is thus independent of the instrument orientation.

The sample chamber is directly in the sample path and has a small volume. There is therefore a very short response time for the OXYMAT channel. Vibrations frequently occur at the place of measurement and may falsify the measured signal (noise). A further microflow sensor (10) through which no gas passes acts as a vibration sensor.

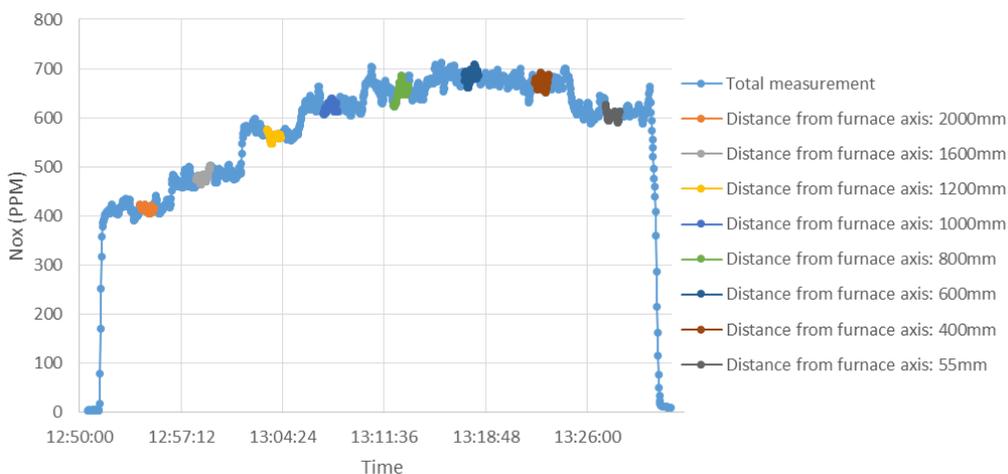
Its signal is connected to the measured signal as compensation.



## Chapter 3

# Data processing

After taking the measurements at CIUDEN, all the data is processed. During a day of measurements, the data acquisition has logged continuously. The first task is therefore filtering the data to extract the useful part. Figure 3.1 is an example of a measurement taken during the air setting of NO<sub>x</sub>. The total measurement shows the continuous signal logged while the probe was inside the furnace. During the measurements the times are noted when the probe was in a certain position. Now from the total data, excerpts of one minute are taken to be used for the results. The average and standard deviations are taken from the excerpts. These excerpts are plotted in figure 3.1 with a different colour. Between these measurements the probe is moved, as can be seen by the change in values between the sample times.



**Figure 3.1:** *NO<sub>x</sub> measurement in port 6.*

After the data is filtered and the averages are calculated at every measurement point, plots are made of concentration to axis distance. This gives a good visualization of the condition in the furnace, ready for further interpretation.

### 3.1. Measurement inaccuracies

IFRF studies carried out with the sample probe show that there are three main families for error sources:

- Statistical error.
- Error due to the sampling.
- Error due the analysers.

Each error source is elaborated here:

### Statistical error

Due to the instability of the flame the values of the concentration of the chemical species varied considerably during the measuring time. The data collected in the report are the average of the values measured for each sampling point over a minute. In normal conditions the standard deviation of the same set of data is the most relevant source of error and assumed as the uncertainty of the measurement. However in some cases different error sources become more important.

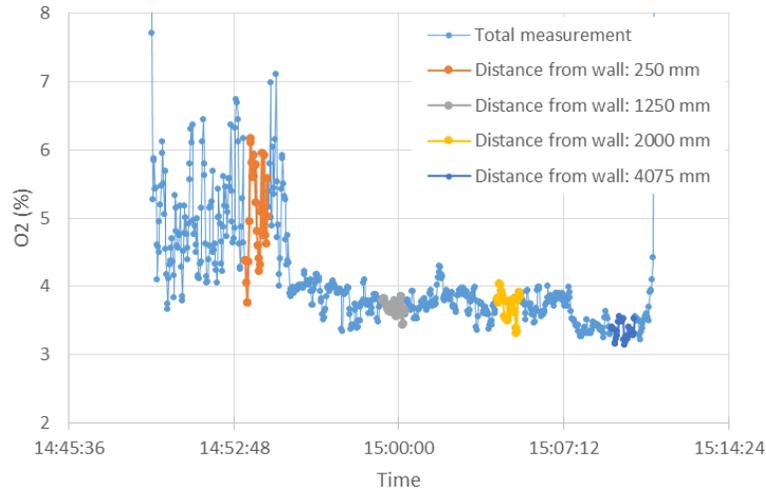
### Error due to the sampling

In the process of sampling several processes influence the quality of the data.

#### Leakage

The analysed gas sample can be contaminated by gas coming from a different location than the measurement point. This could be caused by leakage in the suction line. This way ambient air is mixed into the sample. To prevent this the line is regularly checked for leakages by closing the inlet and observing the flow meters. For an air tight system the flow meters will drop to zero. This way it is insured air leakage is minimized and should not have a big influence on the results.

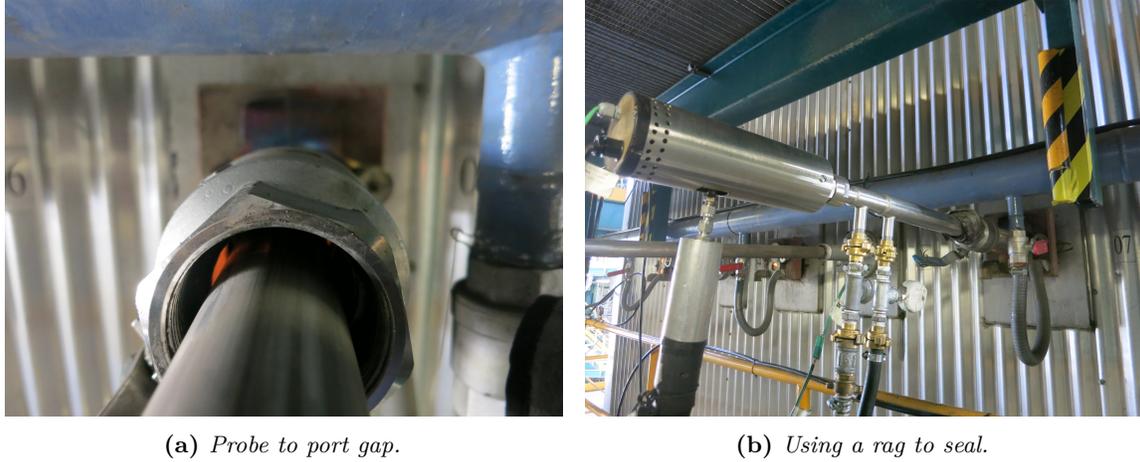
An other way of contamination is by ambient air flowing into the boiler through the insertion hole of the probe. As the boiler is operated on lower than ambient pressure and the probe does not fully close the insertion hole, air flows in. This effect is most clearly seen in the measurements close to the furnace wall. The data of an oxygen measurement away from the burner is shown in figure 3.2. A continuous measurement is taken while the probe is in the furnace, the coloured sections represent logged measurements at defined positions. In between these measurements the probe is moved. The first measurement is taken close to the wall, large fluctuations are observed which are not present in measurements closer to the furnace axis. At this location these fluctuations are not to be expected. The probe is sucking in ambient air, with higher oxygen concentration, disturbing the measurements. This problem is minimized in later measurements by sealing the port with a rag around the probe. The gap and its solution are visible in figure 3.3.



**Figure 3.2:** *Leakage in oxygen measurement.*

#### Positioning

The positioning of the probe is done using a tape line, accurate to 1mm. Given the difficulties of measuring in the industrial environment, it is clear the uncertainties are higher. For instance it is difficult to keep the tape line exactly straight, also the probe bends because of its own weight. Therefore a total horizontal measuring error of 15mm is assumed. Concerning the vertical position of the tip of the probe inside the furnace, also some uncertainties are present. When the probe is deep inside the furnace it leans downwards and the tip is in a lower position than the horizontal line



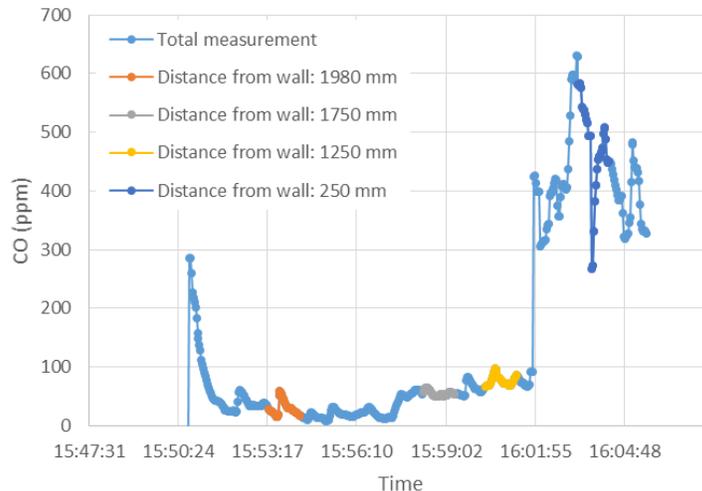
**Figure 3.3:** Air leakage.

from the port. When the probe is close to the walls, the big part hanging outside of the furnace is pushing down the tail and hence pushing up the tip. As a result to these considerations, an uncertainty on the vertical position of the tip of the probe of 50mm is present.

Next to the measuring error it is important to note that the probe does not take its sample from exactly one point. As the probe is sucking in gas, it is taking in gas from all around the inlet. The data captured should therefore not be considered as the exact composition at the measuring point but more as an average of a region centred around the probe inlet. On the basis of experimental experience this region is assumed to have a radius of 2.5 cm.

### Contamination of the probe

During all measurements it is important to review the data for unexpected behaviour. For example the data of figure 3.4 is recovered. The measurement is taken far away from the burner where no combustion is taking place. A concentration of CO above 100 ppm is a signal combustion is still taking place, as it is an intermediate species. Because the samples are taken far away from the flame, it is expected to have low levels of CO. For the first three measurements this is correct, however the last point shows high levels of CO. This signals something might have distorted the measurement. It turned out a piece of burning ash found its way inside the suction probe. The burning ash was still reacting and provided the high concentration of CO visible.



**Figure 3.4:** Ash burning inside the probe.

### Error due the analysers

The gas analysers are calibrated and maintained twice a year by an external company. The instruments behave linearly and are calibrated with two measurement points. Because a different system is used for all individual species, cross-sensitivity can be minimized. This is especially important for in-flame measurement because of the large amount of species present. The error of the analysers is normally below 0.1 % for O<sub>2</sub> and CO<sub>2</sub>. The analysers for NO<sub>x</sub> and CO are below 5 ppm.

For SO<sub>2</sub> the value of the measured concentration is less accurate. Being soluble in water, a part of the gas is lost during sampling due to the condensation in the dryer of the analysing system. The evaluation of the loss of SO<sub>2</sub> is very difficult. In similar conditions with the same sampling system, IFRF determined that the concentration of SO<sub>2</sub> is underestimated by about 100 ppm.

Compared to other uncertainties, the error introduced by the analysers are considered very low. Therefore under normal conditions they are negligible. However during measurements the two following cases had a considerable impact on the results.

During the experimental campaign high concentrations of SO<sub>2</sub> were measured in the coal oxy-combustion cases. Since the analyser was programmed to give the data logger a signal between 0 and 1900 ppm, information was lost because it was out of range. Nevertheless the analyser was programmed to measure up to 5000 ppm, which covered all values. Therefore it was possible to record manually the values of SO<sub>2</sub> from the display of the analyser. These less accurate manual readings are presented in the results. Unfortunately these readings have no statistical information and have to be presented without standard deviation.

A second issue occurred with the CO<sub>2</sub> analyser with range up to 100%. During the analysis of the data, unrealistic high values of CO<sub>2</sub> were encountered. In order to find an explanation the reliability of the instrument was assessed. At first it looked like there was an inaccurate calibration of the analyser but going deeper in the investigation it became clear that the end of scale was not steady and the values corresponding to 100% CO<sub>2</sub> varied by few percentages during the use of the analyser. For some days a characterization of the changes of this end of scale was tried but no evident trend was found.

In the final results, data taken with this instrument (CO<sub>2</sub> readings higher than 30%) represent the most reasonable value. This means the value measured is corrected with the most probable end of scale. The uncertainty of these measurement have been increased to 4.5% to take into account the possible variation of the end of scale.

### 3.2. Normalization

To provide comparable results between the different settings, the gas compositions are normalized. This means converting the concentrations of species to mass per energy produced. The normalization takes into account differences in mass flow at the stack and the amount of energy produced by the coal. The calculation uses equation 3.1, dividing the mass of species *i* produced per hour by the energy burned per hour.

$$C_i^N = \frac{x_i \rho_i \dot{V}_{Stack}}{\dot{m}_{coal} NCV} \quad (3.1)$$

Where:

$C_i^N$	Normalized production of species <i>i</i>	[mg/MJ]
$x_i$	Molar concentration from gas analysers	[mol/mol]
$\rho_i$	Normalized density (273.15 K, 1013.25 mbar)	[g/Nl]
$\dot{V}_{Stack}$	Normalized volume flow of the stack	[Nl/h]
$\dot{m}_{coal}$	Mass flow of coal to the four burners	[kg/h]
NCV	Net calorific value of the coal	[MJ/kg]

In the calculations normalized gas volumes are used, this means a gas on atmospheric pressure and 0 °C. To calculate the normalized density, the molar volume at normal conditions is used together with the molecular mass of species  $i$ . CIUDEN has provided data to calculate the average volume flow in the flue gas line and information about the coal. Together with our measurements of gas composition the normalized values are calculated.

### 3.2.1 Error of normalization

Because the calculation introduces several uncertainties an estimation is made for the error margin. In this study only the quantifiable errors, i.e. statistical fluctuations, are taken into consideration. It must be kept in mind that the sources of errors are more than these, therefore the calculated error estimations are very optimistic. The real uncertainties in an industrial rig are higher than the ones in this report. The statistical fluctuations analysed are from the species concentrations and the volume flow. Using rules for error propagation the standard deviations are combined into a single error estimation which is presented together with the results.

IFRF measurements of species concentration in the boiler are averaged over one minute. As concentrations fluctuate constantly inside the boiler, the standard deviation is often much higher than the error of the instrument. Depending on the measurement and species this can amount to the biggest uncertainty. It is therefore an important factor in the error estimation for the normalization. In IFRF measurement reports the standard deviation is always given.

The stack flow is taken as the average during stable operation in the designated setting. Uncertainties in the flow affect the end results of the normalization. Data received from flow sensors is not always accurate, also the mass flow is fluctuating during operation. Therefore the standard deviation of the volume flow through the stack is calculated.

# Chapter 4

## Results

All acquired results are presented in tables and supplied to all the partners. To support the data, figures are made of species concentration to boiler position. In comparison of the different measurements, emphasize is on port 6 and 7 as these help study the properties of the flame. Port 7 being close to the burner shows an early stage of the combustion process while port 6, farther away from the burner, shows a more developed situation. Next to port 6 and 7, port 32 and 40 are observed. These ports are located farther away from the burners where the composition remains mostly constant. Measurements here give an approximation of the produced flue gas. In the following sections every species measured is discussed. In the end the normalized values of emissions are presented.

### 4.1. Oxygen

Oxygen, together with the coal, are the main reactants of combustion. Over the length of the flame the oxygen concentration will decline. Oxygen concentrations are also a strong factor in NO<sub>x</sub> production. High temperatures together with high oxygen concentrations increase NO<sub>x</sub> production. Low NO<sub>x</sub> type burners are therefore designed to regulate oxygen concentrations and avoid peak temperatures.

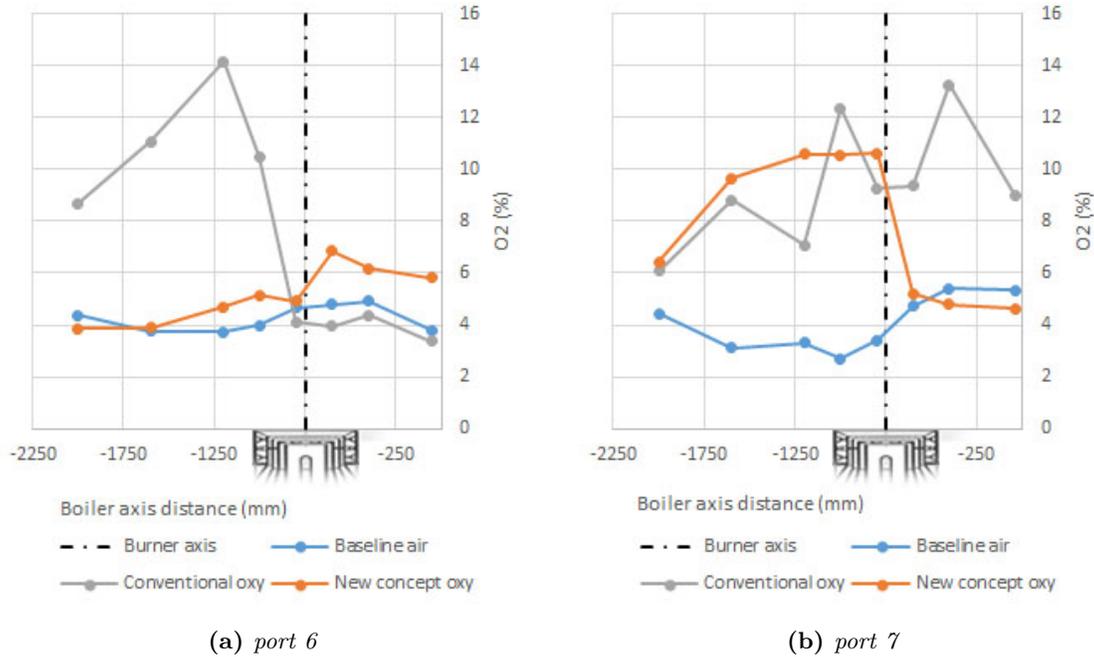
Figure 4.1 shows the oxygen concentrations in front of the burner. All measured concentrations are lower than the oxygen content of input flows at the burner. Concentrations are declining from port 7 to port 6 signifying the measurements are in-flame. The oxy cases generally show higher oxygen levels in front of the burner. This is because the recycled flue gas is injected with higher oxygen concentrations than the oxygen content of air. For the conventional oxy case, in port 7, peaks are from the secondary oxygen flow which is concentric with the primary feed surrounding it.

In port 7, the new oxy shows higher concentrations left of the burner axis, in port 6 this oxygen content has declined. For the conventional oxy setting this high concentration is visible in port 6, although no measurement further away from the burner is available. From these results it seems the gas is reacting faster on the right of the burner axis, consuming the oxygen. As the furnace is not symmetric around the burner, different flow characteristics are possible. Higher levels of turbulence could cause better mixing and faster reaction rates. Looking at the temperature measurements in the report of W.Broenink [4], higher temperatures are measured at the boiler axis which also result in higher reaction rates.

In the new oxy concept, the oxygen concentration is increasing to the right of the burner. This could be caused by a recirculating flow in front of port 7 containing burnt gases with low oxygen.

Before the exit of the boiler the oxygen level is about the same in oxy and conventional combustion (the figure is omitted due to confidentiality). Higher levels are observed near the boiler wall, these can be explained by air leaking from the measurement ports. During the last measurements the port was sealed, preventing leakage, therefore the new oxy concept measurements shows a more

consistent value. Near the axis of the boiler values approach 3% excess oxygen as specified by the control room.



**Figure 4.1:** Oxygen measurements in front of the burner.

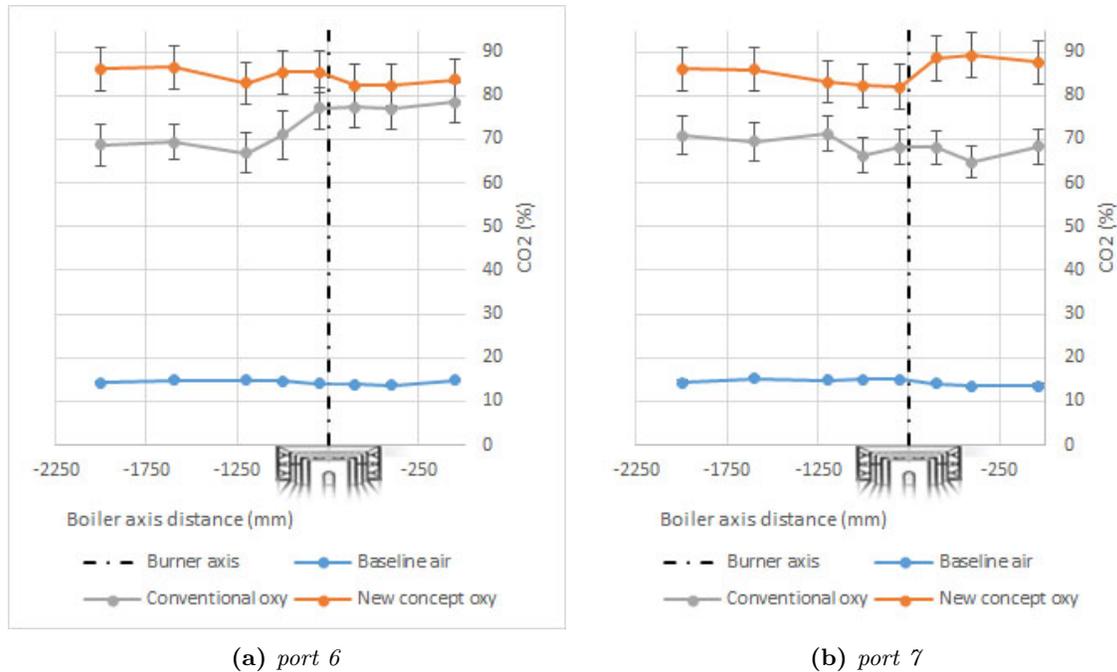
## 4.2. Carbon dioxide

Carbon dioxide is the main product of combustion and is therefore an indicator for the conversion. An increase in concentration signifies combustion has taken place. An important goal of the project is to achieve high concentrations of carbon dioxide in the flue gas for carbon capture and storage purposes. This makes the measurements of carbon dioxide concentrations crucial to the project.

Carbon dioxide measurements are plotted in figures 4.2 and ???. Error bars are made visible because of the uncertainty of an improper functioning gas analyser. It is however clearly visible the the oxy modes produce much higher concentrations of carbon dioxide. In the flame region it varies in a range from 65% to 90%.

For the conventional oxy case, an increase in concentration near the boiler axis is observed from port 7 to 6. This corresponds with the consumption of oxygen visible in previous graphs. In the new concept oxy mode a decrease is measured to the right of the burner. Just as with the oxygen measurements, this could indicate a recirculation zone. To the left of the burner, the new oxy concept shows an increase of carbon dioxide corresponding to the decrease of oxygen. Overall the highest concentrations are examined in the second oxy mode.

At the exit of the boiler, oxy modes measure concentrations between 70 and 85 percent and oxygen mode measures around 15 percent. However the difference in carbon dioxide between oxy modes is questionable, measurements of other parties show comparable concentrations for both modes. Therefore the difference might partly be caused by the error of the IFRF gas analyser. The figures at the exit of the boiler are again omitted because of confidentiality.



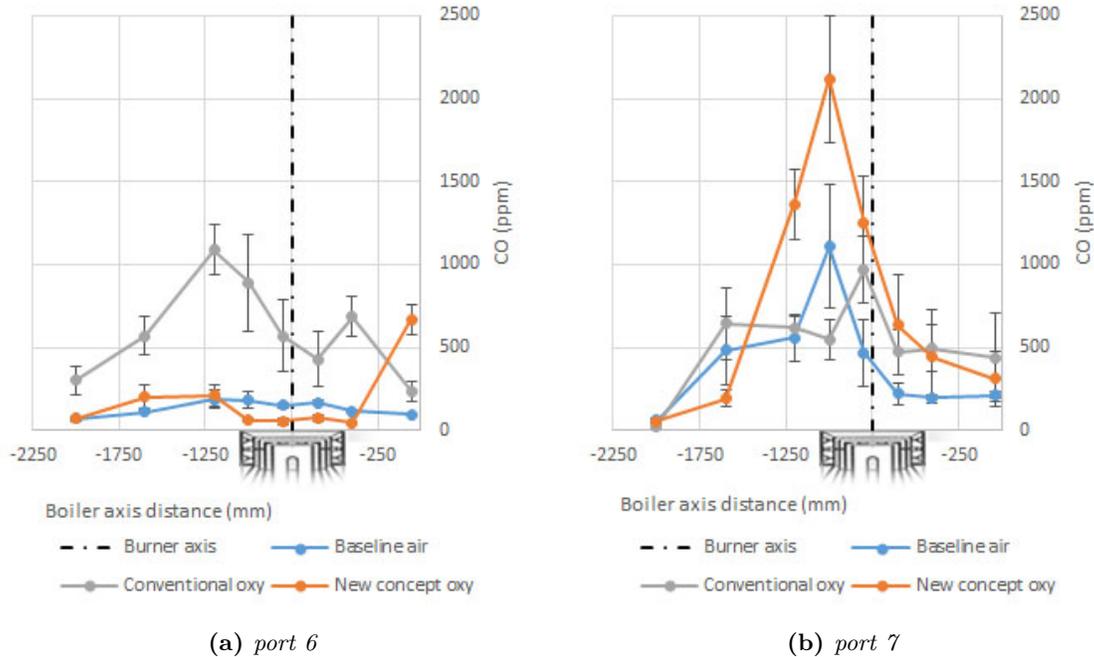
**Figure 4.2:** Carbon dioxide measurements in front of the burner.

### 4.3. Carbon monoxide

Carbon monoxide is an intermediate species in the combustion process. Therefore high concentrations signify combustion is taking place. When concentrations drop below 100ppm the reaction is considered to be finished. Higher concentrations in the flue gas remain when there is not enough oxygen injected.

In figure 4.3 measurements in front of the burner are presented. Error bars are visible as the standard deviations of the measurements are high. Because carbon monoxide is an intermediate species it fluctuates along with the combustion. As the flame is turbulent, concentrations fluctuate strong over time. The averages therefore are only an indication of the actual situation.

All settings show higher concentrations to the left of the burner. In previous graphs it was already visible there was still more oxygen available for reaction here. To the right most of the oxygen is already consumed and the reaction is slowing down. Carbon monoxide concentrations drops quick from port 7 to 6 in air and new oxy mode, however for conventional oxy mode it remains steady. This indicates the flame is farther away from the burner in the conventional oxy mode. This is also visible in the temperature plots of the report by W.Broenink [4]. Temperatures in port 7, close to the burner, show very low values.

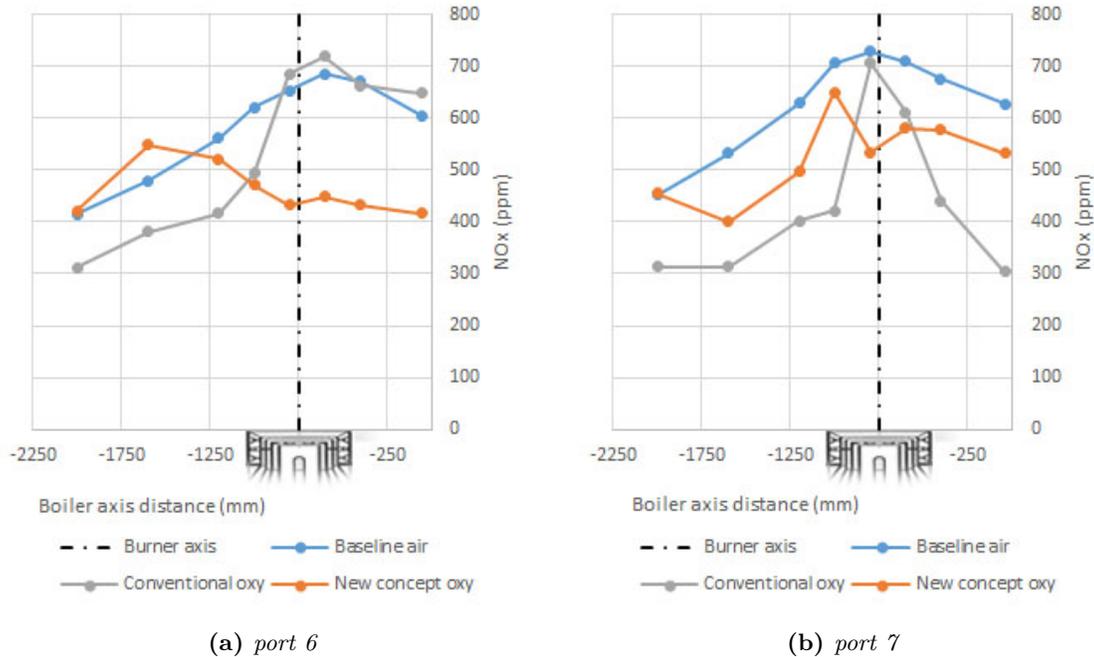


**Figure 4.3:** Carbon monoxide measurements in front of the burner.

#### 4.4. Nitrogen oxides

One of the most important emissions of energy production are nitrogen oxides (NO<sub>x</sub>). There are generally three accepted mechanisms for NO<sub>x</sub> formation: prompt NO<sub>x</sub>, fuel NO<sub>x</sub> and thermal NO<sub>x</sub>. Prompt NO<sub>x</sub> is important in lower temperature combustion processes, but is generally much less important at higher temperatures. Fuel NO<sub>x</sub> is formed by the oxidation of organo-nitrogen compounds contained in the fuel. Thermal NO<sub>x</sub> production increases exponentially with temperature, above about 1,100 °C it is generally the predominant production mechanism. Effort is made to decrease the production of NO<sub>x</sub> by using low NO<sub>x</sub> burner designs. These burners are designed to avoid peak temperatures and high oxygen concentrations in the flame. By using pure oxygen in oxy-coal mode, the concentration of nitrogen is also drastically lowered.[2]

In figure 4.4 the measured values of NO<sub>x</sub> in front of the burner are presented. It is visible, especially in port 7, concentrations are highest at the burner axis. The temperature of the conventional oxy mode is very low at port 7[4], meaning it should produce little thermal NO<sub>x</sub>. The peak at the burner axis is therefore a result of fuel NO<sub>x</sub>. The fuel is injected at the burner axis, explaining the position of the high concentrations. In the other modes the NO<sub>x</sub> is composed of both thermal and fuel NO<sub>x</sub>. Concentrations in air and new oxy mode settle down after port 7. In conventional oxy mode the concentrations increase a little. In earlier graphs it was already visible the flame is farther away from the burner, therefore higher fuel concentrations remain at port 6, creating fuel NO<sub>x</sub>. The air mode measures higher average concentrations, this is most likely caused by the nitrogen content in air converting to NO<sub>x</sub>.



**Figure 4.4:** Nitrogen oxides measurements in front of the burner.

## 4.5. Sulphur dioxide

Coal-fired power plants are the largest human-caused source of sulphur dioxide ( $\text{SO}_2$ ), therefore it is important to monitor. Coal naturally contains sulphur, and when coal is burned, the sulphur combines with oxygen to form sulphur oxides.

In figure 4.5 are the graphs of sulphur dioxides measurements in front of the burner. The results are already quite flat in the first port in front of the burner. Therefore most of the sulphur dioxide seems to have already been produced before our first measurements. In the S2-O1 case, in port 6, a low concentration is measured close to the boiler wall. However as there is no statistical data available for these measurements it is unsure how reliable this point is.

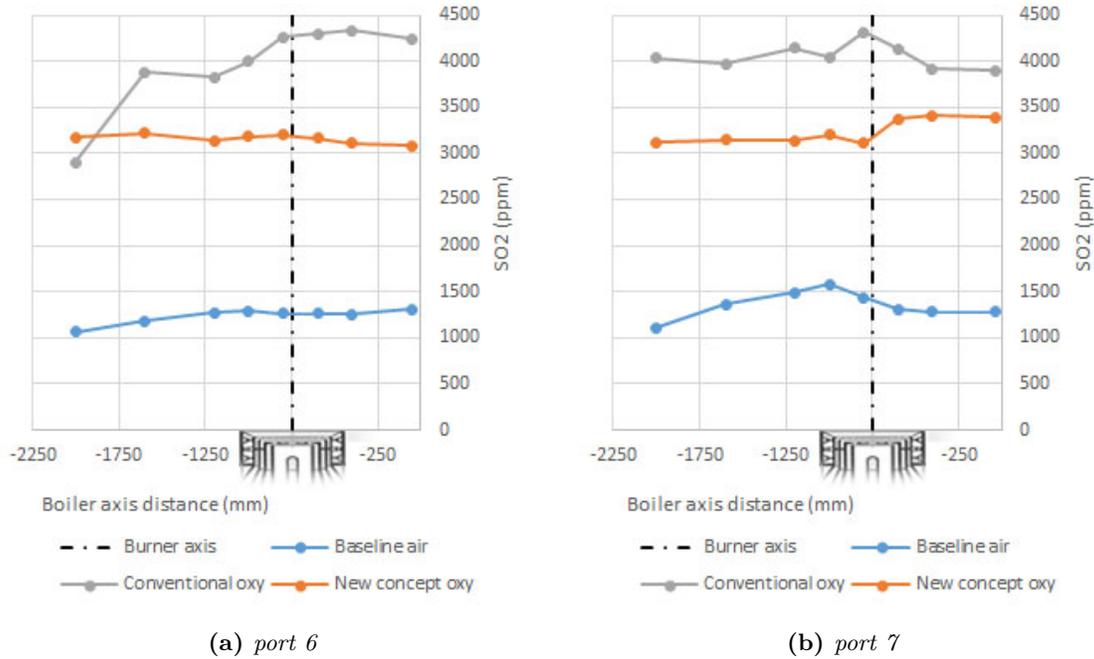


Figure 4.5: Sulphur dioxide measurements in front of the burner.

## 4.6. Normalization

Because power production and volume flows are different between the settings, concentrations are normalized for comparison. All species concentrations are converted to mass per energy produced. For this comparison emphasize is on the flue gas composition to compare emissions of the different settings. Data is also added from average European power plants burning hard coal. The data is taken from the education database of PE International and is produced by measured or calculated data taken from national inventory reports, emission inventory data bases, utility companies and other sources. The results of normalization are in figure 4.6, the values of the axis are omitted due to confidentiality. It should be noted the values on the vertical axes of the different species are very different. The error bars are based on the calculations with standard deviation of the collected data. These error estimations are very optimistic.

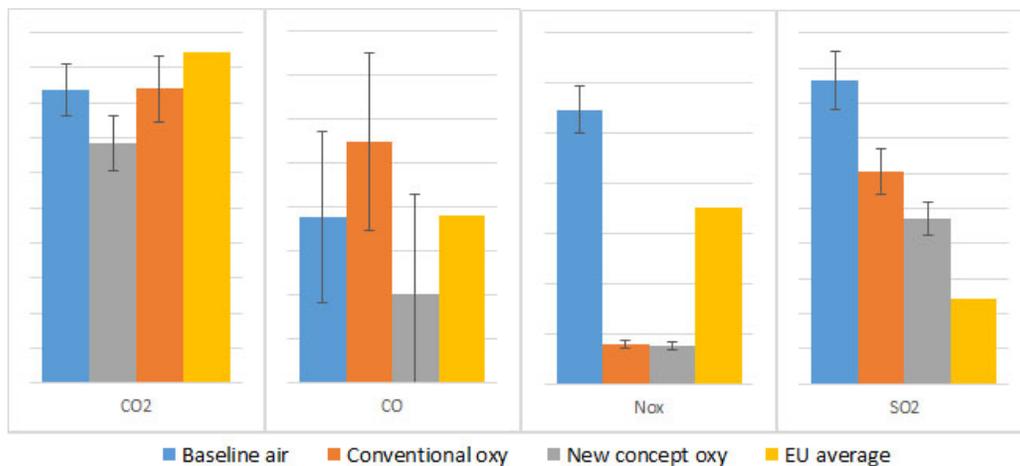


Figure 4.6: Normalization results (mg/MJ).

Differences in carbon dioxide and carbon monoxide can mostly be explained by the error margin. Taking into account these error margins, all the normalized values are in the range of the European

average.

Looking at nitrous oxide production some big differences are detected. Air case produces by far the most NO<sub>x</sub>, higher than the European average. Most European power plants use flue gas cleaning processes for removing NO<sub>x</sub> from exhaust gases. During the tests in CIUDEN, no NO<sub>x</sub> removal was in operation, explaining the high values. For both oxy modes NO<sub>x</sub> readings are very low, with no considerable difference between the two. Apparently the second oxy mode burner settings did not affect the NO<sub>x</sub> production. From the results it can be concluded the process of using recycled flue gas does indeed drastically decrease NO<sub>x</sub> production.

Sulphur dioxide measurements are all higher than the European average. During the measurements CIUDEN did not operate any sulphur dioxide removal system. However often European power plants use scrubbers to remove sulphur dioxide from the flue gas. Therefore IFRF measurements show higher results. The new oxy mode shows the lowest SO<sub>2</sub> production, indicating this setting decreases the conditions for SO<sub>2</sub> production. A big contribution is also caused by the sulphur content in the coal. Each measurement day a sample of the coal is taken and put through an analyser. Higher sulphur content of the coal have resulted in more sulphur dioxide in the flue gas.

## Chapter 5

# Conclusions

During a measurement campaign undertaken for the Relcom project, IFRF has made in-flame measurements for a large scale experiment of oxy-fuel combustion. During the campaign some difficulties occurred with the carbon dioxide and sulphur dioxide measurements. Error estimation have been computed and provided with the data. The data has been provided to the project partners and used for evaluation of CFD simulations, flame stability assessments and scaling rules. In this report the results are analysed and three settings are compared. First is the baseline air mode, second the conventional oxy combustion and third a new concept in which the oxygen concentration of inlet flows is altered.

Using the measurement results the flames in the different settings are characterised. The conventional oxy mode showed a flame positioned farther away from the burner than the other settings. The effect of multiple burners in the boiler is also visible in the results. Measurements are not symmetric around the burner axis. In general the reaction speed seems higher to the middle of the boiler, which is between two burners. This could be caused by higher temperatures and better mixing. Carbon dioxide concentrations have been found to be around 80% in the flue gas. Unfortunately the measured values are not very accurate because of instrument malfunction. However the goal of reaching high carbon dioxide concentrations in the flue gas is reached. Using oxy fuel combustion, the flue gas is more suitable for processes like carbon capture. This provides a good base for future implementation of the technology.

Next to the species concentration, also normalized values for the emissions are calculated. The values are compared to average European data from PE International. The results for air case showed the experiment produced large quantities of nitrogen oxides and sulphur dioxides. This is mostly explained by the fact the facility was not operating NO<sub>x</sub> and/or SO<sub>2</sub> reducing instruments during the experimental campaign. Comparing the oxy mode to air, the drop in NO<sub>x</sub> production is most clear. Because the oxy fuel technology does not use ambient air, with high nitrogen content, nitrogen oxide production is drastically lowered.

The project has had a good result, it has been verified oxy-coal combustion is possible on a large scale. This means it can be implemented into real operating power plants within a reasonable time. Implementations of the technology will be an important step in reducing worldwide CO<sub>2</sub> emissions for the coming years. Now it is proven to be technically feasible the next step is to make it economically interesting for energy companies to implement the technology.

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