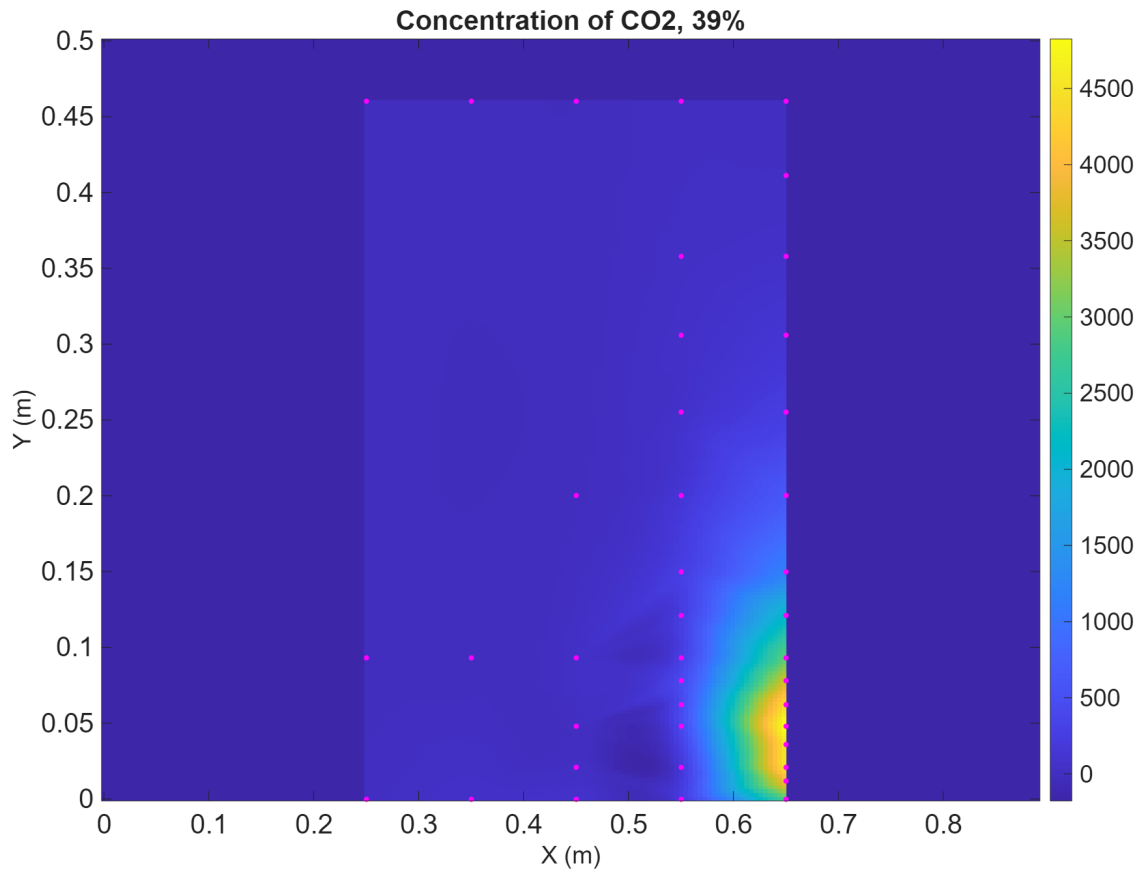




Secondary air jet penetration in large-scale CFB furnaces

Experiments in a cold flow model

Master's thesis in Innovative and Sustainable Chemical Engineering

Linnéa Forsman & Simon Lindström

DEPARTMENT OF ENVIRONMENTAL AND ENERGY SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY

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MASTER'S THESIS 2026

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Cover: Concentration plot of the movement of secondary air for a percentage of 39%
secondary air.

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Abstract

This thesis investigates secondary air jet penetration in CFB boilers by using a cold-flow model. Fluid-dynamic scaling using Glicksman's simplified scaling laws allowed the results to be scaled to hot conditions representative of an industrial boiler. Four different cases with different secondary air velocities were considered and one additional case without secondary was used as a reference. For the four cases, secondary air was injected at two height levels with one additional level representing flue gases. One of the secondary air injection ports was substituted with CO_2 as a tracer gas. Different secondary-to-primary air ratios were studied while maintaining a constant total volumetric airflow. The movement of secondary air and solids was evaluated using gas tracing, pressure transducers and solids circulation rate measurements. The results indicate that higher shares of secondary air yield a deeper penetration and dispersion into the riser. However, it was also determined that a higher proportion of secondary air resulted in lower lateral dispersion towards the sides. Regarding the distribution of solids, a dense bed is more easily attained with increased secondary air (and thus reduced primary air). The solids circulation rate was found to decrease for higher proportions of secondary air.

Keywords: Circulating Fluidized Bed Boilers, Secondary Air Injection, Gas Tracing, Fluid-dynamical scaling, Gas Penetration and Dispersion

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Linnéa Forsman, Simon Lindström, Gothenburg, June 10, 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
FB	Fluidized Bed
FG	Flue Gas level, bottom level in S13
ku	Kurtosis
PSD	Dimensionless particle size distribution
R1-2	Secondary air injection, top level in S13
R3	Secondary air injection, middle level in S13
sk	Skewness
std	Standard deviation

AI-Use

We as authors want to be transparent regarding the use of Artificial Intelligence (AI) in this thesis. AI, more specifically ChatGPT and Claude, have been used for the purpose of assisting with coding. In addition, the thesis was reviewed using ChatGPT to correct for spelling mistakes, unclear formulations and to ensure that information is not repeated unnecessarily throughout the thesis.

Nomenclature

Below is the nomenclature of parameters and greek letters that have been used throughout this thesis in alphabetical order:

Parameters

a	Splashing zone decay coefficient	$[m]$
$A_{\perp}$	Cross-sectional area	$[m^2]$
$A_{\perp}^{DC}$	Cross-sectional area in the down-comer	$[m^2]$
$A_{\perp}^{riser}$	Cross-sectional area in the riser	$[m^2]$
c_p	Heat capacity	$[\frac{J}{kg \cdot K}]$
C	Concentration	$[\frac{kg}{m^3}]$
$C_{i/j}$	Concentrations for S13 (i) and Amagerværket (j)	$[\frac{kg}{m^3}]$
C_{peak}	Peak concentration for respective case	$[\frac{kg}{m^3}]$
C_s	Concentration of solids	$[\frac{kg}{m^3}]$
$\overline{d_p}$	Average particle diameter	$[m]$
D	Equivalent riser diameter	$[m]$
D_{50}	Distance between L_{50} and the peak concentration point	$[mm]$
g	Gravitational constant	$[\frac{m}{s^2}]$
G_s	Externally circulating solids	$[\frac{kg}{m^2 \cdot s}]$
Δh	Height difference	$[m]$
h_{HOFOR}	Height of the boiler at Amagerværket	$[m]$
h_{S13}	Height of S13	$[m]$
ku	Kurtosis	$[-]$
K	Transport zone decay coefficient	$[m]$
L	Length	$[m]$
L_{Cold}	Length of the cold unit	$[m]$
L_{Hot}	Length of the hot unit	$[m]$

L^*	Scale factor for length	[-]
L_{50}	A line at 50% of the peak concentration for respective cases	[mm]
m	mass	[kg]
m^*	Scale factor for mass	[-]
m_{Cold}	Mass used in the cold unit	[kg]
m_{Hot}	Mass used in the hot unit	[kg]
ΔP	Difference in pressure	[Pa]
P_d	Penetration depth	[mm]
$\overline{P_d}$	Mean penetration depth	[mm]
PSD	Dimensionless particle size distribution	[-]
sk	Skewness	[-]
t_{Cold}	Time used for the cold unit	[s]
t_{Hot}	Time used for the hot unit	[s]
t^*	Scale factor for time	[-]
Δt	Time difference	[s]
u	Velocity	$[\frac{m}{s}]$
u_{air}	Velocity of the air	$[\frac{m}{s}]$
u_{CO_2}	Velocity of the carbon dioxide	$[\frac{m}{s}]$
u_{mb}	Minimum bubble velocity	$[\frac{m}{s}]$
u_{mf}	Minimum fluidization velocity	$[\frac{m}{s}]$
$u_{mf\ Cold}$	Minimum fluidization velocity for the cold unit	$[\frac{m}{s}]$
$u_{mf\ Hot}$	Minimum fluidization velocity for the hot unit	$[\frac{m}{s}]$
u_{prim}	Velocity of primary air	$[\frac{m}{s}]$
u_{sec}	Velocity of secondary air	$[\frac{m}{s}]$
u_t	Terminal velocity	$[\frac{m}{s}]$
u_0	Fluidization velocity	$[\frac{m}{s}]$
$u_{0\ Cold}$	Fluidization velocity for the cold unit	$[\frac{m}{s}]$
$u_{0\ Hot}$	Fluidization velocity for the hot unit	$[\frac{m}{s}]$
U_{TOB}	Velocity at the top of the boiler	$[\frac{m}{s}]$
$\dot{V}$	Volumetric flow	$[\frac{m^3}{s}]$
$\dot{V}_{tot}$	Total flow	$[\frac{N \cdot m^3}{h}]$
y_i	Distance i in the y direction	[mm]

Greek letters

ε_g	Gas fraction	$[-]$
λ	Conductivity	$[\frac{W}{m \cdot K}]$
ρ	Density	$[\frac{kg}{m^3}]$
ρ_{air}	Density of air	$[\frac{kg}{m^3}]$
ρ_{CO_2}	Density of carbon dioxide	$[\frac{kg}{m^3}]$
ρ_g	Density of gas	$[\frac{kg}{m^3}]$
$\rho_g \text{ Cold}$	Density for solids in the cold unit	$[\frac{kg}{m^3}]$
$\rho_g \text{ Hot}$	Density for solids in the hot unit	$[\frac{kg}{m^3}]$
ρ_s	Density of solids	$[\frac{kg}{m^3}]$
ϕ	Particle sphericity	$[-]$

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1

Introduction

Robust and environmentally friendly energy systems are increasingly important in today's socio-economic climate. According to the Paris agreement, a maximum increase of 2°C above pre-industrial temperatures is allowed. In the year 2024, the energy sector contributed to 24.6 % of the total greenhouse gas emissions [1]. Therefore conventional power plants burning fossil feedstock such as coal and gas need to shift to renewable alternatives. However, renewable energies such as solar and wind have more fluctuating energy outputs compared to more traditional fossil sources [2]. Another renewable energy pathway is the conversion of biomass into heat and power.

Boilers are one option for this conversion of biomass. However, conventional boilers struggle to convert biomass into thermal energy due to their heterogenous physical and chemical characteristics [3]. Also, a growing industrial interest in biomass as feedstock means an increased competition between different energy uses and synthetic products. Fluidized bed (FB) technology is able to utilize low-grade biomass which makes it highly competitive. In FB furnaces, the bed material consists of bulk solids (sand-like fine particles in a boiler, or metal powders in a cold flow model), which provide momentum transfer for the mixing of the solid fuel phase (biomass, solid waste) and enhanced heat transfer. This arrangement provides two main characteristics: ability to handle fluctuating fuel, and good mixing [4]. The latter implies that FB units are able to maintain a uniform temperature profile in relation to other alternatives [3]. There are two types of FB boilers: bubbling fluidized beds (BFB) and circulating fluidized bed (CFB). This thesis will focus on CFBs. One of the main issues with replacing coal and gas power plants is their flexible ability to regulate energy to fit the energy demand. CFBs are an efficient option as they are also flexible while reducing emissions. Additionally, they could also reduce the size of landfills due to their ability to convert waste-derived fuels [1].

A CFB boiler requires continuous airflow for combustion, which is provided in stages (called primary and secondary). Primary air is introduced vertically from the bottom plate while secondary air is applied at an angle from the sidewalls. The main reasons for introducing secondary air are to minimize emissions (mainly NO_x) and aid in combustion.

This work aims to determine the effect that different secondary-to-primary ratios have on the gas-solids flow. More specifically, the gas penetration and dispersion and the solids concentration and circulation rate are studied. The obtained data is intended to provide **HOFOR** with information on secondary air behaviour, potentially aiding the sintering of solids in the cyclone duct at the Amagerværket CFB boiler. For this, experiments are carried out in a downscaled model using copper particles which can be up-scaled into large-scale hot conditions.

2

Theory

2.1 Circulating Fluidized Bed boilers

In Sweden there exists approximately 130 FB boilers that contribute to the energy sector. This large number of boilers is due to the abundance of biomass. However only a smaller portion ($\approx 20\%$) of these FB boilers are of the CFB type [5]. This does not mean that 80% of FB boiler energy is provided by BFB units. Since the installation and operational costs for CFBs are higher than BFB boilers, they are often of capacities $\geq 100MW_{th}$ and even higher for units that are implemented into combined heat and power (CHP) systems. In comparison, BFB units are typically $\geq 10MW_{th}$, which means the overall provided energy from CFBs is drastically higher than 20% [4].

FB boilers are efficient and maintain an ability to operate with a wide variety of different fuels. This makes them an attractive alternative in the heat and power industry since they also have high solids and gas mixing rate and thereby good contact between phases [6]. CFB and BFB boilers are useful for different applications due to their respective characteristics. Because of their higher gas velocity, CFBs utilize solids circulation and show a superior specific thermal capacity (MW/m^2) compared to that of BFBs [4]. Since this thesis considers CFB boilers, BFB boilers will not be considered further.

The main parts in a CFB boiler are the riser, cyclone and loop seal. Combustion ideally takes place in the riser only, whereas the cyclone separates the solids from gas. After combustion, flue gases exit at the top of the cyclone while solids are recirculated back into the dense bed by the loop seal. CFB boilers also utilize secondary air inlets which have an inclination to avoid solids going the opposite way. Another important part of CFB boilers are the fuel injection ports. These differ between units where some fuel injection ports drop the material onto the bed while other units inject the fuel which aids the mixing of fuel and bed solids.

Because of the entrainment (where particles are dragged from the bed) and circulation of solids with a high heat capacity, the temperature profile of a CFB boiler is relatively homogenous. This means that hotspots can be avoided which allows for better heat and mass transfer, low NO_x formation, higher efficiency, low pressure drop, scalability, controllability and robustness [1]. However, CFB units are also complex to design, operate and model making them a costly alternative [1].

Ensuring adequate penetration of secondary air into the furnace is important for mixing and consequently, boiler efficiency. Hence, understanding to which degree the secondary air penetrates into the furnace is crucial. Although computational fluid-dynamics (CFD) simulations can be used to study this, such modelling is still not mature enough to reliably describe the highly turbulent flows and the movement of solids that are present in CFB boilers [4]. Therefore work was done experimentally in this thesis to acquire results of higher reliability. These results were then compared to values obtained by **HOFOR**'s CFB boiler, Amagerværket, in Copenhagen.

2.2 Combustion in Circulating Fluidized Bed boilers

Combustion is an exothermic reaction where a fuel and an oxidant are required. Typically, air is introduced to oxidize fuels to CO_2 and H_2O . There are many types of fuel used in commercial CFB boilers. Both coal and biomass are common alternatives with different compositions. Using either of these two fuels comes with different technical challenges when operating the boiler. Many companies, for example **HOFOR**, choose to operate with woody biomass as it is the more environmentally friendly option. In comparisons with coal, biomass contains a greater amount of certain elements (O, H, N and more), moisture and volatiles [7]. These differences in composition demand different considerations for design and operation.

A difficulty for plants choosing to operate with biomass is the fluctuations in the properties of feedstock [8]. To ensure high efficiency, operation parameters need to be adjusted to accommodate differences in moisture content between each batch. The higher volatile content of biomass is also important to consider. During combustion, volatiles are released as gases with shorter residence times than char (the solid combustible remaining after devolatilization of the fuel) [9]. This means that they are likely to leave the riser uncombusted, and even by-pass the first levels of secondary air. In this case, air and volatiles meet in the cyclone which results in a delayed combustion and an inefficient recovery of the released heat.

This reduction in efficiency occurs because sand is unable to aid in the heat transfer to the same extent in the cyclone which is an issue since air is a much poorer conductor of heat compared to sand. Two parameters are of interest when discussing the heat transfer, thermal inertia $m \cdot c_p$ and conductivity λ . The mass used in the thermal inertia was calculated via the density and a theoretical volume set to 1 [m^3]. Thermal inertia describes how difficult it is to heat or cool a specific material while the conductivity describes the material's ability to transfer heat. Both parameters are reported for air and sand in Table 2.1 obtained from [10] and [11]. As seen in Table 2.1 both thermal inertia and conductivity are larger for sand than air.

Table 2.1: Comparison of heat capacity and conductivity for sand and air at 291 K.

	$m \cdot c_p [\frac{J}{K}]$	$\lambda [\frac{W}{m \cdot K}]$
Air	1207.56	0.02624
Sand	$2\,184 \cdot 10^6$	0.4

There are other consequences of this misplaced combustion like the reduced efficiency of heat extraction to the steam production. A considerable amount of energy is lost because the majority of water piping is along the riser and not the cyclone. Also, this misplaced combustion, and sudden increase in temperature, leads to a propagation of undesired chemical reactions like corrosion and slagging [12]. Additionally, these chemical phenomena could cause a build-up of solids in industrial boilers.

Sintering of solids can become a problem for operation of large-scale CFB boilers. The agglomeration can block the primary airflow causing an uneven fluidisation which affects the combustion and cost companies large amounts of money due to the required down-time and equipment repair [13]. Amagerværket's duct between the furnace and cyclone suffers from the build-up of a solids sintering shown in Figure 2.1. One possible explanation for these deposits is the temperature increase in the cyclone caused by the aforementioned burnout in the exit zone and cyclone rather than along the riser. Gaining an understanding of the mixing in the furnace and ensuring a full burnout could potentially reduce the likelihood of sintering.

**Figure 2.1:** Sintering of solids in the duct of Amagerværket, provided by HOFOR.

One of the advantages of utilizing CFB boilers for combustion is their low formation of pollutant NO_x gases [14]. NO_x is a term used to denote a collection of different gases, mainly nitric oxide (NO) and nitrogen dioxide (NO_2). These gases are formed through oxidation according to the equations listed below.



NO_x gases are undesired because of their dangerous properties that have been proven to have negative effects on both the environment and humans [15]. Currently in Sweden there exists a $\frac{50kr}{kgNO_x}$ tax to incentivize companies to reduce their emissions of NO_x [16]. CFB boilers' ability to maintain low NO_x emissions is therefore appealing both from an emission and economic standpoint.

2.3 Fluidization in Circulating Fluidized Bed boilers

Fluidization can be defined as the process in which solid particles are suspended in a gas or liquid causing the bulk of solids to take on a fluid-like state [17]. To achieve fluidization the airflow needs to reach or exceed the minimum fluidization velocity (u_{mf}) which differs depending on the particle and fluid properties. In CFB boilers fluidization occurs in the loop seal and in the riser. The fluidization in the loop seal allows the solids to move towards the riser. In the riser fluidization is used to distribute the fuel throughout the dense bed through lateral mixing, see **Fuel Mixing**, subsection 2.4.1.

The regimes that exist in a CFB boiler are Bubbling fluidization and Turbulent fluidization.

- 1 *Bubbling fluidization*; the velocity is above u_{mf} and large gas bubbles are formed that causes the solids to move more vigorously. Volume does not change much compared to the volume at u_{mf} . This regime occurs in the loop seal but not in the riser.
- 2 *Turbulent fluidization*; for this type of fluidization, high gas flows cause entrainment in the dense bed and circulation through the boiler. A requirement for this entrainment is that the terminal velocity (u_t) of solids is exceeded. u_t is the velocity of when the forces on the solid are in balance, so that the solid remains suspended. Commonly occurring phenomena in *Turbulent fluidization* are voids of gas in varying shapes, turbulent flows of solid clusters and a lack of a uniform surface of the bed.

If the fluidization velocities are too low and in a narrow cross-section, problematic fluidization phenomena can occur. A common issue is the formation of slugs, or *slugging*. There are mainly two types of slugging, axial and flat. For both types of slugging gas bubbles tend to form in the bed [17]. These then grow increasingly in size the further up the bed they travel. This growth is due to the collision or coalescence of bubbles. Axial *slugging* is when fine particles fall down the wall, surrounding a gas pocket that spreads across the vessel. Flat *slugging* is where a layer of particles rest on top of a void fraction. Eventually, these particles fall into the bubble removing it entirely. However the bubble reappears almost instantly and the process is repeated. Slugging is not an issue for industrial CFB boilers as large cross-sections and silica sand is used. However, in the S13 unit slugging could potentially become an issue when operating the butterfly-valve. The butterfly-valve is explained further in **Circulation Rate**, subsection 3.1.1.3.

Achieving and sustaining homogeneous fluidization is complicated and highly dependent on pressure drop. When using solids of uniform size, the relationship between $\log \Delta P$ and the velocity is linear within the range of $0 \frac{m}{s}$ to u_{mf} [1]. Once u_{mf} is reached the pressure drop remains constant. For the case when a wide variety of solid sizes are used it is difficult to determine when fluidization appears. This is because of the hysteresis behaviour caused by the finer solids passing through the spaces of the larger solids and thus fluidizing earlier. As a result u_{mf} is found through extrapolation. Reaching u_{mf} is important to achieve a fluidized bed. The solids of this thesis are more uniform in size compared to the solids used in industrial boilers which makes fluidization easier to achieve and maintain.

As mentioned in **Combustion in Circulating Fluidized Bed boilers**, section 2.2, sintering can occur at high temperatures. Sintering in a fluidized bed is problematic as the behaviour of the fluidized bed will change. Sintering causes the solids to agglomerate which hinders the air from penetrating, creating a defluidized zone. To investigate at which temperature a bed defluidizes, Gluckman et al. [18] investigated sintering close to the u_{mf} using copper. In the experiment, a fluidized bed was heated slowly until the bed defluidized. It was found that at elevated temperatures (however not high enough to melt the solids) the bed first got more viscous and as a result defluidized. This shows that applying temperatures above a certain limit can compromise the quality of fluidization which makes sintering not only an issue in combustion but also for fluidization.

2.4 Mixing in a Circulating Fluidized Bed boiler

To get an efficient and complete combustion good contact between gas, solids, air and combustible gases is crucial [1]. Insufficient mixing causes an increase in the emissions of hydrocarbons, CO and NO_x [1], [19]. The mixing in a CFB boiler is complex due to possible non-uniformity in the flow of gases and maldistribution of fuels. Bed solids clusters, distribution of solids and wall interactions are some of the parameters that can affect the mixing and further complicate the prediction of how mixing is carried out in a CFB boiler. When investigating the interaction between gas and solids mixing, axial and radial dispersion are commonly used. The gas dispersion varies with superficial gas velocity, bed solids concentration, type of solids, gas composition and when there are variations in the circulation flux of solids.

2.4.1 Fuel Mixing

Fuel mixing is essential for efficient performance in CFB boilers [20]. Ensuring efficient horizontal mixing is crucial for optimal combustion as an incomplete mixing results in unbalanced concentration and temperature fields, yielding maldistributed heat extraction and increased pollutant emissions. Proper vertical mixing promotes complete combustion because of the sufficient contact time between oxygen and fuel. The fuel injection ports in a CFB are constructed to promote mixing via ensuring an even distribution of solids [21]. According to Basu [21], several injection ports are needed for fuels with higher volatile content since they devolatilize near the port, which causes an uneven temperature profile in the boiler. When the fuel is injected, fuel particles tend to remain at the bottom part of the riser due to their large size and density compared to solids [20]. However during combustion of the fuel, reduction of size and density can favour that the char moves into the upper freeboard instead.

2.4.2 Solids Mixing

The bed solids behaviour is important when operating a fluidized bed. For this reason, Geldart classified four groups of particles and their expected behaviour [1]. Classification is based on the mean value of the particle diameter and density. The particles used in fluidized bed boilers belong to group B and the particle diameter and density range within $40 < \overline{d_p} < 500 \mu m$ and $1.4 < \rho < 4 g/cm^3$. Fluidization of these solids at low velocities is characterized by large energetic bubbles with minimum bubble velocities (u_{mb}) in the similar range of that of the minimum fluidization ($u_{mb} \cong u_{mf}$).

The mixing of solids in the riser of a CFB boiler can be sectioned into three zones characterized by the solids behaviour [4]:

1. Dense region; at the lowest region of the riser. Here the fluidization velocity exceeds u_t , resulting in gas fluctuations which creates the dense bed [4]. The mixing is characterized by air bubbles rising through the dense bed, which causes solids to be lifted in their wake while other solids are submerged in the

surrounding emulsion [3], [4].

2. Splash zone; exists above the dense bed surface. Solids in the splash and transport zone can either be considered as clustered or dispersed. In the splash zone, bubbles explode, and clustered solids exit and eventually re-enter the bed [4]. The clustered phase exceeds the dispersed phase and the main back-mixing occurs here.
3. Transport zone; exists in the upper section of the riser. The transport zone can be explained by the core-annular structure. At the core, solids are carried upwards whereas back-mixing occurs via solids moving towards the wall, getting stuck and falling back down to the bed in the annular structure [4]. As the movement of solids is complex, understanding the flux of the cross-section is important. The concentration of solids determine the behaviour of the movement of solids. At higher parts in the furnace, where concentrations are lower, transport is nearly pneumatic. In the transport zone the disperse phase of solids dominate.

The movement of solids in a CFB boiler is complex since they experience complex residence time distributions because of the back-mixing and axial dispersion [1]. Additionally, the attrition between solids deteriorate the particles making them smaller. This means operators need to add more solids to compensate for the decrease in solid size and cyclone losses.

Distribution of solids in the transport and splashing zone can be described by decay coefficients. These describe the decrease in solids concentration with height in the riser. A higher decay coefficient means a lower entrainment at the dense bed and consequently less material at the top of the unit.

2.4.3 Gas mixing

Similar to **Solids Mixing**, predicting gas mixing is complex since there are many variables to consider. One of these is the geometry of the boiler, as the cross-sectional size and shape of the furnace will impact the gas-solids flow pattern [1]. Other factors such as air velocity, wall roughness, and solids concentration will also have an effect on the movement of gas. However, these variables impact on the gas mixing is not yet fully understood.

As previously mentioned, there are three zones in a CFB riser where the solids behaviour varies which implies that the gas mixing also varies throughout each zone. Thus, the fluid-dynamics of the gas should be investigated separately. Concepts such as the core-annulus structure which was described in **Solids Mixing**, subsection 2.4.2, also make it difficult to understand how gases behave in the freeboard.

The main mechanisms in gas mixing is convection and dispersion. Convection contributes to the mass transfer due to the overall movement of the system and dispersion is the transport that occurs due to turbulence, concentration gradients and velocity fluctuations [6]. Risers of CFB boilers are typically rectangular in shape and in one study [6], it was found that lateral dispersion and gas velocity increased with height along the longer side of the cross-section. For the shorter side, lateral dispersion remained almost constant which could be an indication that the mixing rate has reached a maximum value [6]. However, an increase in the gas velocity impacts parameters that are interdependent which makes it difficult to comprehend how the flow parameters influence the environment and therefore the movement of gas.

2.4.4 Air Injection

2.4.4.1 Primary Air

Since the main focus of this thesis is secondary air, primary air will only be mentioned briefly. Primary air is supplied to the unit through the windbox (bottom of the riser) which allows for fluidization. The primary air is introduced through nozzles to achieve a large pressure drop and to avoid solids from entering the air system, see Figure A.1 available in *Appendix 1*. Both primary and secondary air functions as both fluidization and reaction agents. Maintaining a reasonable proportion between primary and secondary air is important to avoid defluidization.

2.4.4.2 Secondary Air

As a reminder, one reason for introducing secondary air in CFB boilers is to improve mixing and consequently combustion. Utilizing secondary air comes with many other advantages for CFB boilers: the combustion of volatile matter in the freeboard and an improvement of gas mixing above the bed are two discussed by Pallarès [22]. The secondary air also creates a more uniform temperature profile by ensuring that combustion occurs staged throughout the riser [23]. Introducing more stages of secondary air is beneficial for better control and an even smoother temperature gradient, see Figure 2.2. It can also avoid the formation of hot spots as the combustion occurs uniformly throughout the riser. This is also helpful in reducing NO_x emissions [22]. Industrial units typically have two-three levels of secondary air for economic reasons. Both in terms of equipment and the supply of air. Also, the implementation of secondary air results in less excess air use [3]. This is because the lateral mixing achieves a more uniform fuel distribution resulting in lower operation costs and higher efficiency.

Secondary-air behaviour in CFB boilers can be described by two key phenomena. The first part is the penetration into the furnace, which ideally would be high. This would result in better contact between volatiles and oxygen. The second part considers dispersion throughout the cross-section, which would preferably be approximately cone-shaped so that the combustion would continue to occur gradually, see Figure 2.3. If the air dispersed is too wide, combustion would occur at high rates at one height leading to the formation of hot spots. In the case where it is too narrow, contact between air and volatiles is minimal resulting in low rates of combustion. Additionally these gases would eventually meet and combust in the cyclone instead, an issue discussed in **Combustion in CFB boilers**, section 2.2.

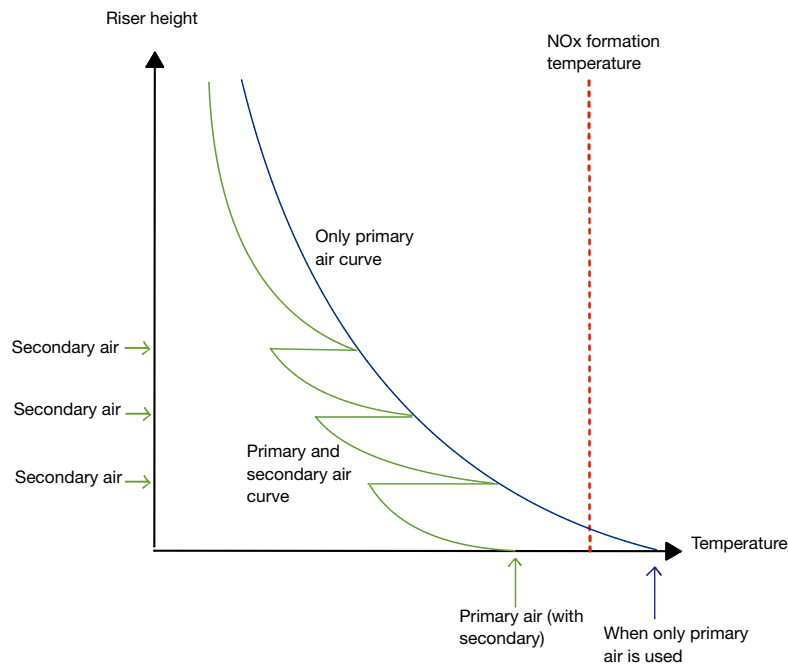


Figure 2.2: Schematic illustration of the temperature profile: air staging of secondary air (green) and only primary air (blue). The dotted red line shows the NO_x formation temperature.

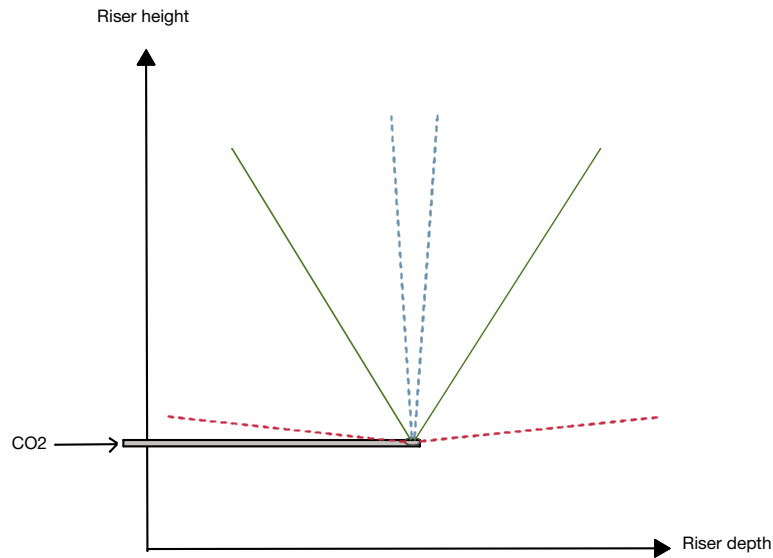


Figure 2.3: Desired shape of the dispersion of secondary air. In the figure a probe is used to inject the CO_2 to make the desired dispersion easier to comprehend. The dotted red line shows a scenario of when the gas is dispersed too wide and the dotted blue line shows the scenario of when it is too narrow. The desired shape would be between those exemplified by the green lines.

Introducing the right ratio between primary and secondary air is critical to the operation of CFB boilers as too little secondary air results in an unfinished combustion of volatiles whereas an excess of secondary air means that combustion occurs at high rates near the inlet [24]. Having excessive combustion near the inlet means formation of NO_x will be severe due to the high temperatures. Thus, finding the right amount of secondary air needed for complete combustion while maintaining an even temperature gradient is ideal.

According to [4], the entrainment of solids are hindered when secondary air is applied into the freeboard and improved when injected directly into the dense bed. However, industrial CFB boilers typically introduce secondary air above the dense bed. The reason for this is to avoid producing high amounts of NO_x . If secondary air was to be introduced at lower points in the furnace, the nitrogen would react with it and create NO_x . Consequently, nitrogen should be allowed time to create N_2 before secondary air is introduced.

2.5 Scaling

Obtaining data from industrial units is both difficult and expensive. Therefore using fluid-dynamically down-scaled units is beneficial. To allow for accurate modelling a set of scaling laws are required. This means that continuity and momentum balances need to be re-written into dimensionless form [4]. To preserve similarities between the laboratory and industrial model, some dimensionless parameters need to be kept constant. Glicksman suggested some of these scaling laws as two sets, full and simplified [25]. The simplified set can be found in Equation 2.3.

$$\frac{u_0^2}{gD}, \frac{\rho_s}{\rho_g}, \frac{u_0}{u_{mf}}, \frac{L}{D}, \frac{G_s}{\rho_s u_0}, \phi, PSD \quad (2.3)$$

Regarding CFB boilers, scaling laws allow for a more controlled investigation where fluid-dynamics can be replicated. By substituting conventional CFB boiler agents (such as hot air and silica sand) with alternative substances (for S13, ambient air and copper), the dimensionless numbers are maintained and enables modelling at smaller scale. A drawback with the fine copper particles used for this set is that they can create strong inter particle forces and static charge that could have an effect on the flow of solids [4].

The cold-flow model used in this project, S13, is scaled to $\frac{1}{13}$ th of a conventional boiler. Meaning that the unit which is around 3 meters in height, models a ~ 40 meter high conventional boiler. This linear relationship is not true for all parameters, hence Glicksman's scaling laws need to be applied when converting for certain parameters. The following equations: Equation 2.4, Equation 2.5 and Equation 2.6 are derived from Equation 2.3. Length, time, mass and their scaling factors are found in Table 2.2 and the values are taken from Djerf's dissertation [4]. The S13 model will be explained in more detail in **Experimental Setup**, section 3.1. The factors are created specifically for the S13 model and a further description of how the scaling factors were created and a more in depth description of the S13 model can also be found in Djerf's dissertation[4].

$$L^* = \frac{L_{Cold}}{L_{Hot}} = \left(\frac{u_{mf_{Cold}}}{u_{mf_{Hot}}} \right)^2 \quad (2.4)$$

$$t^* = \frac{t_{Cold}}{t_{Hot}} = \left(\frac{u_{0_{Cold}}}{u_{0_{Hot}}} \right)^2 \quad (2.5)$$

$$m^* = \frac{m_{Cold}}{m_{Hot}} = \frac{\rho_{g_{Cold}}}{\rho_{g_{Hot}}} \cdot \left(\frac{L_{Cold}}{L_{Hot}} \right)^3 \quad (2.6)$$

Table 2.2: Dimensional scaling factors (*Glicksman's simplified set*)

Quantity	Scaling Factor
Length (L^*)	0.077
Time (t^*)	0.28
Mass (m^*)	0.0016

3

Methods

As mentioned earlier, the purpose of this is to investigate how the gas-solids flow is affected by different secondary-to-primary air ratios. This will be achieved using experiments in a cold-flow model where results will eventually be scaled up to industrial standards. CO_2 was used as a tracer gas to study the transport of secondary air. Varying operating conditions provide data which will be analysed to gain a better understanding of the fluid mechanics related to secondary air penetration in CFB boilers.

3.1 Experimental setup

The cold model used is called the S13 unit which has similar up-scaled characteristics to a 300 MW_{th} boiler and a sampling frequency of 1 Hz. The dimensions of the S13 unit are 3.1 m in height (z), 0.89 m in width (x) and 0.5 m in depth (y), see Figure 3.1. There are three secondary air levels called *R1*, *R2* and *R3*, where *R1* and *R2* have the same injection height into the riser of S13. There is one additional level, *FG*, that aims to replicate recirculated flue gases. The *R1&R2*, *R3* and *FG* levels are placed at heights of 270, 115 and 37 mm at the front ($y=0$ mm) of the unit and 280, 125 and 35 mm at the back ($y=500$ mm) of the unit, respectively. There are 44 secondary air injection ports in total: *R1&R2* have 16 ports, *R3* 12 ports and *FG* 16 ports. The ports are equally divided between the front and the back of the unit. In addition, the S13 unit is equipped with two windows with 48 sampling ports in total, see Figure A.2 in *Appendix 1*. One on the front panel where there are 8 rows and 5 columns and one on the side panel where there are 8 ports in one column. The spacing between the sampling ports is 100 mm.

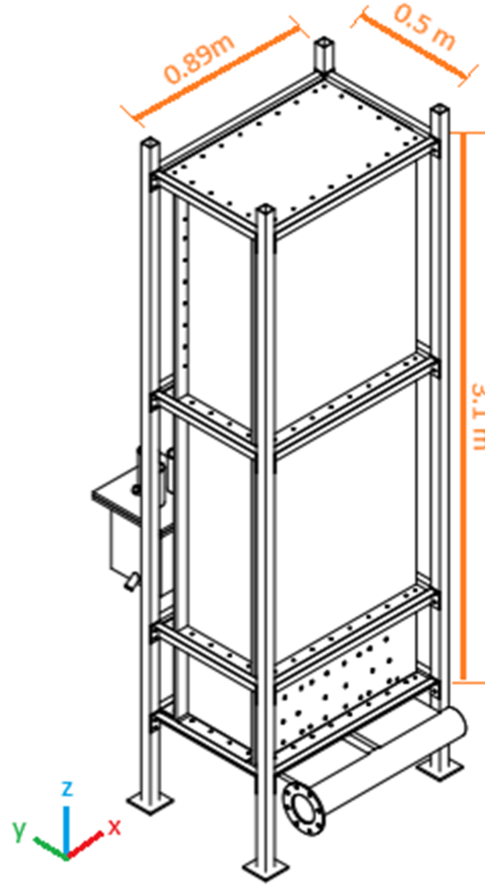


Figure 3.1: The dimensions of the S13 model including directional axes.

The secondary air distribution will be studied in the cross-sectional area of the riser which yields 0.445 m^2 . Ambient air was used as fluidization agent controlled by two fans, one suction and one exhaust. Copper particles with a density of 8920 kg/m^3 and a diameter of $\sim 32 \mu\text{m}$ were used as the solid material due to its scaling properties. This yields a minimum fluidization velocity of $u_{mf} = 0.0045 \text{ m/s}$ and terminal velocity of $u_t = 0.28 \text{ m/s}$ [4].

Selecting an efficient test matrix is challenging as it involves a trade-off between velocity and secondary air. Also, limitations of the physical properties of the unit had to be considered when determining the test matrix. Velocity of secondary air differed between cases but was maintained constant between inlets of secondary air for their respective cases. Inventory was kept constant and the fluidization of the loop seal was set to $\sim 4 \frac{\text{m}}{\text{s}}$. The test matrix had to be determined experimentally and will be presented in **Determining the Test Matrix**, section 4.1.

S13 is effective at resembling the flow conditions of industrial boilers, however there are some differences. Conventional boilers can contain several cyclones to help separate the compounds (in Amagerværket there are two cyclones). However, due to limited space, S13 only uses one cyclone. This means that the flow out of the loop seal of the unit is too high which wears out the bottom plate of the unit, (see Figure A.3 in *Appendix 1*). As previously mentioned, primary air is usually provided in nozzles in conventional boilers. In the S13 unit, no nozzles are used which could have an impact on the fluid-dynamics of the system. Another difference is that many boilers (including Amagerværket) utilize recirculated flue gas for their first level of secondary air. This flue gas contains water which is not something the S13 unit is able to model. Additionally, the lower walls of the riser are usually tapered in industrial boilers which is not the case for the S13 unit. Lastly the injection of CO_2 was performed using a plug with a smaller diameter than the rest of the secondary air inlets which could have an effect on the accuracy of modelling, more on the injection of CO_2 will be presented in **CO_2 Injection and Sampling**, subsubsection 3.1.1.1.

3.1.1 Instrumentation

3.1.1.1 CO_2 Injection and Sampling

During the experimental design of this project, CO_2 tracing was decided to be the most suitable method for evaluating the penetration of secondary air. CO_2 was utilized due to its fluid-dynamics being similar to that of air. Additionally, CO_2 is low in cost, chemically stable and safer to use compared to other alternatives.

CO_2 is injected in the same way as the secondary air using the coupling shown in Figure A.4 in *Appendix 1*. However, to model the velocity of air, high flows of CO_2 are needed. This resulted in concentrations of CO_2 that exceeds the upper measurement limit of the gas analyser. This issue was solved by decreasing the cross-sectional area of the inlet of CO_2 from 17 to 4 mm, thus allowing higher velocities to be used ($u = \dot{V}/A_{\perp}$).

The re-constructed inlet for the CO_2 injection point was set at the second to right position on the R2 level at 590 mm in x-direction, see Figure A.4 in *Appendix 1*. This location was selected to provide insight into horizontal dispersion since measurement points exists in 550 and 650 mm in x-direction. Ideally, the injection point would be set at the centre to get a more holistic view of the horizontal behaviour of the gas. However, since the exit out of the loop seal is in the centre of the riser it was assumed that this would heavily affect the movement of gas.

Due to CO_2 being a denser gas than air, the velocity of injected CO_2 had to be recalculated using Equation 3.1 to correct for momentum. According to the ideal gas law, the molar mass fraction between air and CO_2 is equal to the density fraction $\frac{\rho_{air}}{\rho_{CO_2}} = 0.658$.

$$u_{CO_2} = u_{air} \cdot \frac{\rho_{air}}{\rho_{CO_2}} \quad (3.1)$$

A sampling probe was inserted into the ports at the lowest row of the front and side of the riser (see A.2b and A.2a in *Appendix 1*). This row is placed 0.8 m above the air distribution plate and 0.53 m above the highest injection point of secondary air. The probe was then set at different depths to measure the CO_2 concentration throughout the riser. The depths that were used are: 0, 12, 21, 36, 48, 62, 78, 93, 121, 150, 200, 255, 306, 358, 411 and 460 mm (see Figure A.5, available in *Appendix 1*). At the tip of the sampling probe there is a metal filter that picks up the gas while inhibiting solids from entering the sampling system. Continuously as experiments were running, the gas was transferred from the filter to a gas analyser (*RosemountTM X-STREAM Enhanced General Purpose Compact Table-top Continuous Gas Analyzer (XEGK)*, from **EMERSON**). During operation, data was monitored and obtained in the program **LabView**. The recorded information was then stored on a USB stick.

The selected measuring points for the 39 % of secondary air case is illustrated in Figure 3.2. Possible measurement points are shown as black arrows.

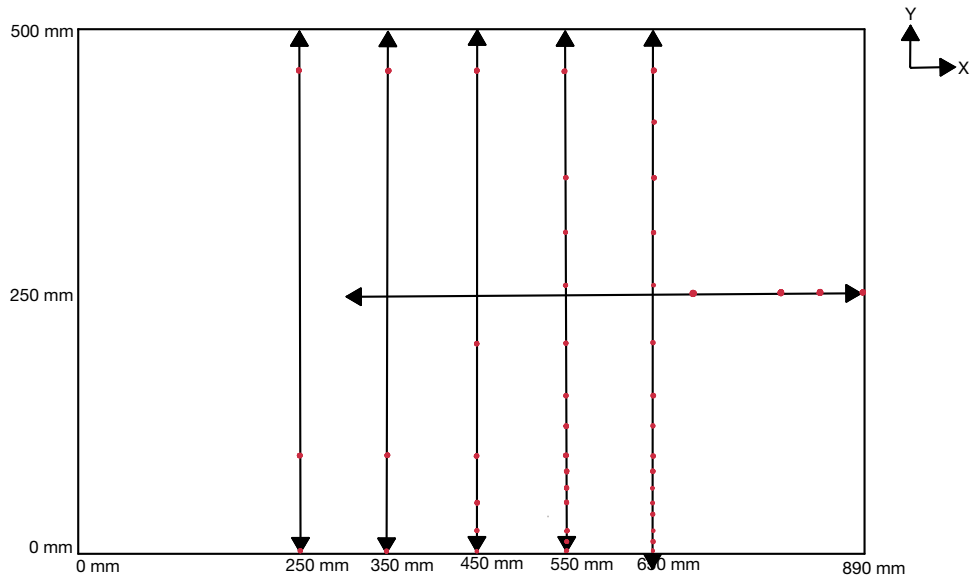


Figure 3.2: Possible measuring points are illustrated by the arrows and the points that were used for 39% secondary air are shown as red points.

3.1.1.2 Pressure Transducers

There are densely distributed pressure transducers throughout the riser of S13. The unit contains 27 pressure transducers which is a lot compared to industrial units that contain around three to six transducers [4]. This gives a higher resolution of the pressure profile which allows for a more thorough analysis. Measuring the distance and pressure difference between transducers means a pressure profile can be obtained. Consequently, Equation 3.2 and thereafter Equation 3.3 can be used to obtain a concentration profile. Equation 3.2 is derived from the general expression for pressure drop (see Equation B.1 in *Appendix 1*).

$$\varepsilon_g = \frac{\frac{\Delta P}{g \cdot \Delta h} - \rho_s}{\rho_g - \rho_s} \quad (3.2)$$

$$C_s = \rho_s(1 - \varepsilon_g) \quad (3.3)$$

There are a few assumptions made for the calculation of concentration. The acceleration of solids is considered negligible and a fully developed velocity profile is assumed. This could be true for the freeboard but not in the dense bed, nor at the duct between the riser and cyclone.

3.1.1.3 Circulation Rate

The circulation rate was measured to quantify the circulation of solids for a given condition. Assuming that the cyclone has a perfect efficiency, the circulation rate is obtained by closing the butterfly-valve at the cyclone exit, see Figure A.6 in *Appendix 1*. When the butterfly-valve is closed, material accumulates on top of the valve over time. Because the valve is porous, an airflow in the opposite direction can be introduced to initiate fluidization. The pressure increases due to the accumulation of fluidized material which can then be measured over time. By extracting the linear region of the pressure transient, the circulation rate can be calculated using 3.4.

$$G_s = \frac{\frac{\Delta P}{\Delta t} \cdot A_{\perp}^{DC}}{g \cdot A_{\perp}^{riser}} \quad (3.4)$$

3.1.2 Experimental procedure

To gain insight into the behaviour of secondary air and the difference between higher and lower proportions, five cases were studied. The velocity at the top of the boiler was kept constant at $0.7 \frac{m}{s}$ while the proportions between primary and secondary air were varied. Cases and their operation parameters are available in *Determining the Test Matrix* section 4.1. To efficiently acquire data from experiments, an experimental procedure was developed to find the possible operation ranges of primary and secondary air.

Measuring points were decided based on the amount of CO_2 , where they were densely spaced for regions with high concentrations. Before taking a measurement, the injection of CO_2 was set to the corresponding flow for each case and allowed sufficient time to stabilize. The pressure taps were then flushed with pressurized air for around 30 seconds to ensure that the pressure transducers were not clogged. This process was repeated between each experiment. Each measurement point containing higher fluctuations and concentrations [$\geq 800ppm$] was sampled for a duration of five minutes while measurement point with lower concentrations [$< 800 ppm$] were measured for three minutes. This was done to allow time for at least three cycles of the CO_2 fluctuations, strengthening the validity of the result.

Once a CO_2 concentration of 500 ppm or lower was found, and after controlling that there were no peaks along the way, the probe was inserted 100 mm deeper to save time. This control was performed visually in the **LabView** program. The last sample was always taken close to the other side of the wall, at 460 mm. Having obtained CO_2 concentrations for different points in one column, the probe was returned to the starting position, after which the operating conditions were changed, and the same approach was applied for a different proportion of secondary air. Once a column was completed, meaning all CO_2 concentrations were acquired, the procedure was repeated for the next column. Finally, four measurements for each case were also taken from the side (for a constant y of 250 mm), shown in Figure 3.2 found in **CO_2 Injection and Sampling**, subsubsection 3.1.1.1.

To obtain pressure profiles and solids circulation rates, another set of experiments needed to be completed. Firstly a case was started where the pressure profile was measured for a duration of three minutes and after this the circulation rate was measured. For all circulation rate experiments, the **LabView** parameters were saved continuously. During the measurements, the valve was closed for 15 seconds and for stabilization purposes there were ten minutes between tests. For each case, five measurements of the circulation rate were obtained.

3.1.3 Scaling

Using scaling calculations a relationship between S13 and conventional boilers could be determined. To convert acquired data and plots to industrial standards Table 2.2 was used. Dimensions, pressures, concentrations and circulation rates were scaled to industrial standards. Conversion of the dimensions is linear (see Equation 3.5).

$$\frac{h_{S13}}{0.077} \approx 13 \cdot h_{S13} \approx h_{HOFOR} \quad (3.5)$$

For the other parameters this is not the case. This scaling is done based on unit conversion and scaling factors from *Glicksman's simplified set*. The unit conversion for the pressure, concentration and circulation rate can be found in Equation 3.6, Equation 3.7 and Equation 3.8.

$$P[Pa] = P\left[\frac{N}{m^2}\right] = \frac{m}{Lt^2} \left[\frac{kg}{s^2 \cdot m}\right] = \frac{0.0016}{0.28^2 \cdot 0.077} \approx 0.265 \quad (3.6)$$

$$C\left[\frac{kg}{m^3}\right] = \frac{m}{L^3} \left[\frac{kg}{m^3}\right] = \frac{0.0016}{0.077^3} \approx 35.05 \quad (3.7)$$

$$G_s = \frac{\frac{\Delta P}{\Delta t} \cdot A_{\perp}^{DC}}{g \cdot A_{\perp}^{riser}} \left[\frac{\frac{Pa}{s} \cdot m^2}{\frac{m}{s^2} \cdot m^2}\right] = \frac{m}{t \cdot L^2} \left[\frac{kg}{s \cdot m^2}\right] = \frac{0.0016}{0.28 \cdot 0.077^2} \approx 0.964 \quad (3.8)$$

3.1.4 Data Processing

To efficiently extract and manipulate data, several **MATLAB** codes were created.

A normal distribution test was done for each CO_2 measurement point to determine whether or not the fluctuations of CO_2 follow a Gaussian distribution. The statistics that were controlled for these tests were the mean, standard deviation (std), skewness (sk) and kurtosis (ku) of the CO_2 concentration. The decision of whether the test is valid, uncertain or invalid was based on the skewness and kurtosis (see Equation 3.9, Equation 3.10, Equation 3.11). What determines the validity of a test is the tolerance where a lower tolerance corresponds to a better test. The ranges for the tests are centred around the normal values of the ku and sk which are three and zero respectively. Three categories were applied because the uncertain tests uses a wide range. This is because the CO_2 fluctuates severely and is influenced by the unpredictable environment in the CFB boiler.

$$\left. \begin{array}{l} -1 < sk < 1 \\ 1 < ku < 5 \end{array} \right\} \text{Valid Tests} \quad (3.9)$$

$$\left. \begin{array}{l} -2 < sk < 2 \\ -1 < ku < 7 \end{array} \right\} \text{Uncertain Tests} \quad (3.10)$$

$$\left. \begin{array}{l} -2 \geq sk \text{ or } sk \geq 2 \\ -1 \geq ku \text{ or } ku \geq 7 \end{array} \right\} \text{Invalid Tests} \quad (3.11)$$

Using a skewness and kurtosis test to determine whether a measurement was of Gaussian distribution was not considered sufficient. Therefore, it was decided to include QQ-plots that show if the data follows a theoretical distribution and if not where the deviations occur in the experiment (see Equation 3.11 found in *Appendix 2*). The std and mean were also included in the evaluation to get an understanding of where the data is centred and the magnitude of fluctuations around that point. Where a low std relative to the mean indicate stable CO_2 signals. Standard deviation could not be set to one specific number since there were differences between measurements. Ensuring the tests are normally distributed means the data is not affected by any underlying errors. Measurements that failed the normal distribution tests were disregarded and removed from the results.

The mass balance was created to corroborate the mass flow of CO_2 between the injection and cross-section of the riser. This was to get an idea if the amount of captured CO_2 was substantial or not and to verify that the majority of CO_2 had not dispersed elsewhere. The code discretizes the riser into a grid where measuring points and their average concentration are designated into a specific box. Depending on the length between measuring points, boxes get different sizes. The code considers only injected CO_2 , meaning that ambient CO_2 was subtracted.

CO_2 maps were also created using **MATLAB**. The average concentration was extracted for each point from their respective proportion of secondary air and the concentration gradient was created by smoothing the surface. This was done so that the concentration between points are estimated based on the measured points.

The points taken from the side of the riser, with a constant y-position of 250 mm, were not included in the CO_2 maps. This is because the smoothing of the surface resulted in a misrepresentation of how the CO_2 is likely to behave. However, between the points taken from the side a difference in concentration was observed. For analysis, a **MATLAB** code was created to compare the concentration at different x-positions. This code was also created to analyse the dispersion along the y-axis. For this, the column with the highest concentrations (x=650 mm) was used. All the cases were plotted in the same graph to visualise how the dispersion differs between cases.

Pressure and concentration profiles were utilized to compare the distribution of solids for different proportions of secondary air. Pressure profiles were obtained using the 27 transducers. Four of these transducers are coupled to the atmosphere instead of the previous pressure transducer. These points are used in the **MATLAB** code as correction points. If points that come before the atmospheric ones are unreasonable the atmospheric point corrects them to align with itself. Pressure outliers that gave unrealistic (negative) concentrations were removed from the graphs.

To quantify the movement of solids, the splashing and transport zone decay coefficients were added to the plots. The decay coefficients are derived from the slope of points belonging to the splashing and transport zone respectively.

For the solids circulation rate, a code was used to extract the linear behaviour of the pressure drop as explained in **Circulation Rate**, subsection 3.1.1.3. Once the five circulation rate measurements for each case were obtained, they were plotted in **EXCEL** to show the spread between the tests to evaluate any potential outliers.

4

Results and Discussion

A few different notations will be used in the results and are listed below for clarity.

- The two horizontal dimensions of the riser are noted with (x), (y) and (z) where (x) is the longer side (890 mm), (y) is the shorter side (500 mm) and the vertical dimension is denoted (z) , see Figure 3.1. The cross-section where measurements are taken will be considered as (z0) and +/- will indicate the direction from that point where + is above the (z0) and - below. When discussing points at (z0), (z0) will not be included.
- Points with constant (x) but changing (y) will be considered columns while the opposite will be considered rows.
- Specific points are denoted as coordinates, such as (x650, y250) where the numbers indicate the length in mm.
- Increasing x-values indicate movement towards the right and increasing y-values indicate positions deeper into the riser.

4.1 Determining the Test Matrix

As previously mentioned, the S13 unit is equipped with two fans, one for suction and one for injection of air. The capacities of the fans in terms of flow and pressure drop limit the maximum flows that can be achieved for different combinations of primary and secondary air. Exploratory experiments were conducted to investigate the possible ranges that could be used, see Figure 4.1. Supplying the same velocity of secondary air as for primary air requires more power from the fans. That is why the larger velocities are only possible with lower proportions of secondary air. It was found that the largest range possible for a velocity at the top of the boiler of $0.7 \frac{m}{s}$, was 60% primary and 40% secondary air. This range was chosen for this thesis as it is desired to replicate proportions of primary and secondary air that are similar to Amagerværket. Their chosen proportion is 50% primary and 50% secondary air. It is important to note that industrial boilers typically operate with velocities close to $4 \frac{m}{s}$, which would correspond to $1.1 \frac{m}{s}$ for S13. As this only achieves lower proportions of secondary air it was not considered in this thesis.

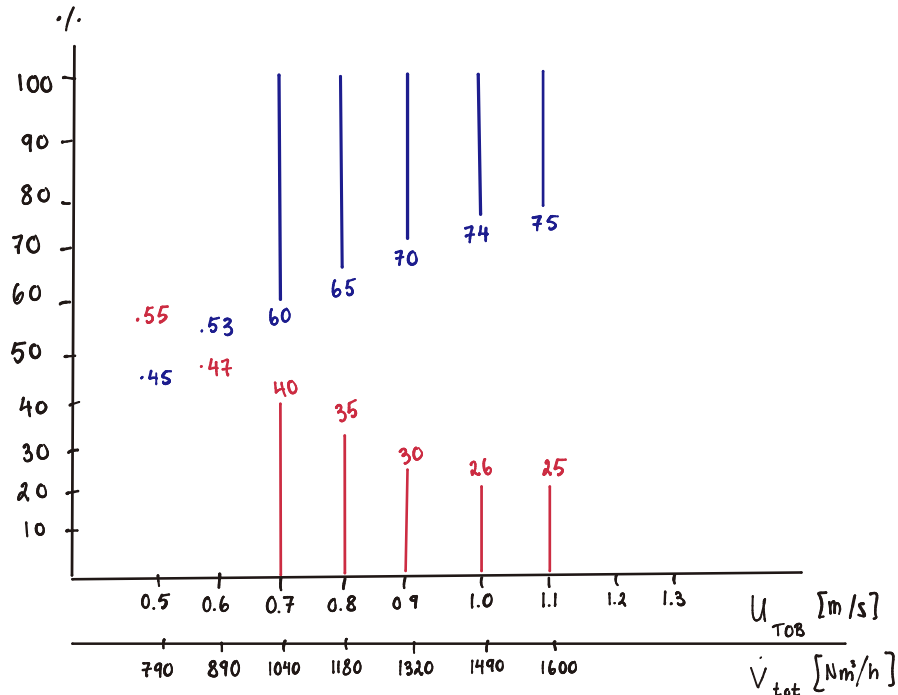


Figure 4.1: Experiments for possible ranges of the S13 unit. The blue lines are possible percentages for primary air and the red ones are for secondary air. There are two x-axes that show the velocity at the top of the boiler (U_{TOB}) and the total flow ($\dot{V}_{tot}$).

From Figure 4.1, five cases of proportions for the velocity $0.7 \frac{m}{s}$ at the top of the boiler (U_{TOB}) were chosen. **Case 0** was considered as a reference with 0% secondary air. **Case 10**, **Case 20**, **Case 30** and **Case 39** consider 10, 20, 30 and 39% secondary air respectively. These cases and their relevant parameters are listed in Table 4.1.

Table 4.1: The cases and relevant parameters that were studied for velocity at the top of the boiler 0.7 m/s.

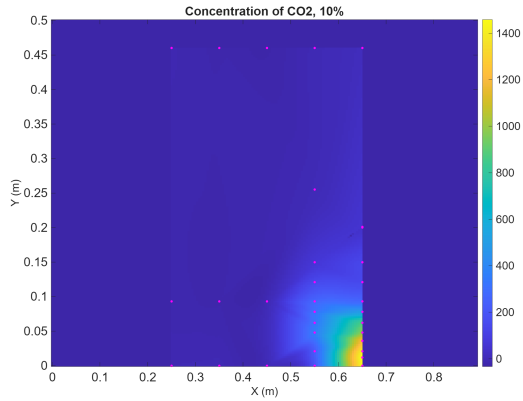
	Total airflow (Nm³/h)	Vel Top Boiler (m/s)	Prim fraction	Sec Total fraction	Sec R1 (Nm³/h)	Sec R1 (m/s)	Sec R2 (Nm³/h)	Sec R2 (m/s)	Sec R3 (Nm³/h)	Sec R3 (m/s)	Sec R4 (Nm³/h)	Sec R4 (m/s)	CO2 in one hole (Nl/min)
Case 39	1121.4	0.7	0.61	0.39	79.52	12.16	69.58	12.16	119.28	12.16	159.03	12.16	6.03
Case 30	1121.4	0.7	0.7	0.3	61.17	9.36	53.52	9.36	91.75	9.36	122.33	9.36	4.64
Case 20	1121.4	0.7	0.8	0.2	40.78	6.24	35.68	6.24	61.17	6.24	81.56	6.24	3.09
Case 10	1121.4	0.7	0.9	0.1	20.39	3.12	17.84	3.12	30.58	3.12	40.78	3.12	1.55
Case 0	1121.4	0.7	1	0	0	0	0	0	0	0	0	0	0

4.2 Distribution of Gas

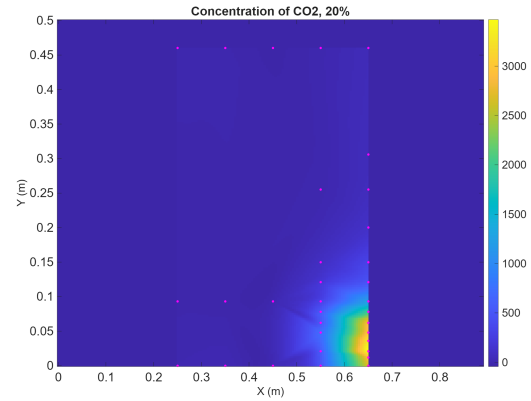
The first results that will be presented are the CO_2 intensity maps for the different proportions of secondary air. The measured points are marked in magenta and the colour bar, with peaks designated as yellow, indicates the acquired concentration in ppm (after subtracting the background concentration, this is the CO_2 concentration in air). For comparison, the colour intensity was normalized meaning yellow always indicated the highest concentration in each case. It was found that a larger proportion of secondary air results in a deeper penetration into the riser, as seen in Figure 4.2. This was expected as a higher proportion of secondary air entails a higher velocity (see Table 4.1 found in *Appendix 2*) and consequently a higher momentum. In addition, cases with a higher proportion of secondary air have a lower velocity of primary air (see Table 4.1 in *Appendix 2*) meaning there is less perturbation for the secondary air injection.

As seen in Figure 4.2 the overall highest concentrations and the peak concentration can be found in column x650 for all cases. Lateral dispersion of gas (in the x direction) appears limited but all tests show significant amounts of CO_2 in column x550. Moving further to the left shows nearly ambient concentrations for all proportions of secondary air. Interestingly, the gas seems to be moving to the right of column x650 which is indicated by the peak existing in this column for all proportions of secondary. Considering that the injection point is in (x590, y0, -z530), it would be reasonable to assume that the peak would exist somewhere between column x550 and x650 but for all cases the concentration is significantly higher in column x650. Therefore there is a possibility that the peak exist somewhere further to the right but this is unknown as it is not possible to measure there.

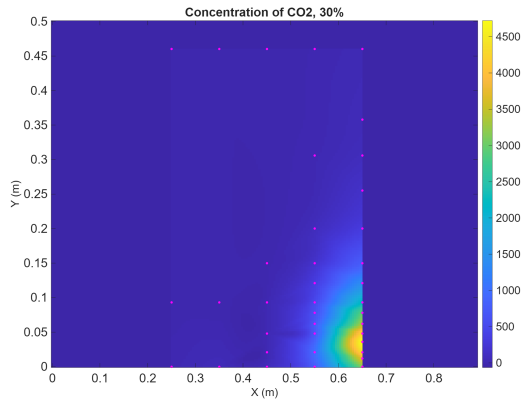
There could be many reasons for this displacement of CO_2 , one of these being the flow from the loop seal. It is possible that the flow from the loop seal is moving the solids and gas to the right, creating the unexpected result. Another potential reason could be an uneven fluidization. If this is the case, solids will tend to move towards the defluidized area [26]. Previous S13 experiments that track the movement of an artificial fuel particle showed that the fuel particle also had a tendency to move towards the right. It is also possible that the reason for the displacement of CO_2 is that it is unable to penetrate the back-mixing layer. This would mean that some portion of CO_2 would be trapped alongside the back-mixing layer, moving along the side of the riser.



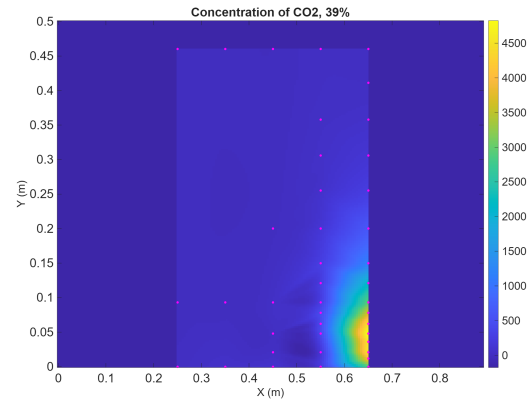
(a) CO_2 intensity map for 10% proportion of secondary air.



(b) CO_2 intensity map for 20% proportion of secondary air.



(c) CO_2 intensity map for 30% proportion of secondary air.



(d) CO_2 intensity map for 39% proportion of secondary air.

Figure 4.2: Intensity maps of CO_2 for the four different proportions of secondary air.

As mentioned in **Experimental Setup**, section 3.1, S13 also contains the possibility of obtaining measurements from the side, at y_{250} . The graphs plotted from these side points are shown in Figure 4.3. Similarly to the concentration profiles, ambient concentration of CO_2 has been removed from all of the measurements. As seen in Figure 4.3 there are comparatively higher concentrations at the point x_{890} for all cases. The point is located at the wall and a trend where the CO_2 concentration plummets before increasing when moving further into the column can be observed. For **Case 10**, **Case 20** and **Case 30** the elevated point at the wall is higher than the points further in whereas for **Case 39**, the concentration is higher in the inner point rather than at the wall. Additionally a trend can be seen in that these concentrations increase for an increased proportion of secondary air except for **Case 39** which has lower concentrations at the points x_{842} and x_{890} than **Case 30**.

The elevated concentrations at the point x890 was an unexpected result as it deviates from the trend shown in the CO_2 maps. As seen in Figure 4.2 the peak concentrations are expected to be located in column x650 relatively close to the wall. The concentration gradually decreases when moving away from the peak as seen in Figure 4.2. Since the profile in Figure 4.3 is relatively consistent throughout all concentrations it is highly unlikely that the cause is an error or an outlier.

These unexpectedly high concentrations at x890 could potentially be due to the discussed inability of secondary air to completely penetrate the back-mixing layer. So that the retained CO_2 in the back-mixing layer subsequently migrates toward x890. As previously mentioned, the concentrations for **Case 30** exceeds those for **Case 39** in x842 and x890. This could be due to that **Case 39** does break the back-mixing layer which could explain these lower concentrations Figure 4.3. Another explanation for why the concentrations at x890 are elevated could be that the CO_2 moves in conjunction with the solids. As previously mentioned, the solids are subject to strong circulations and back-mixing in the riser. Thus the local accumulation of CO_2 near the wall can be explained by CO_2 moving back down together with the back-mixing layer. The increase in concentration at point x690 is likely due to the measurements getting closer to the concentrations found at x650 as seen in Figure 4.2.

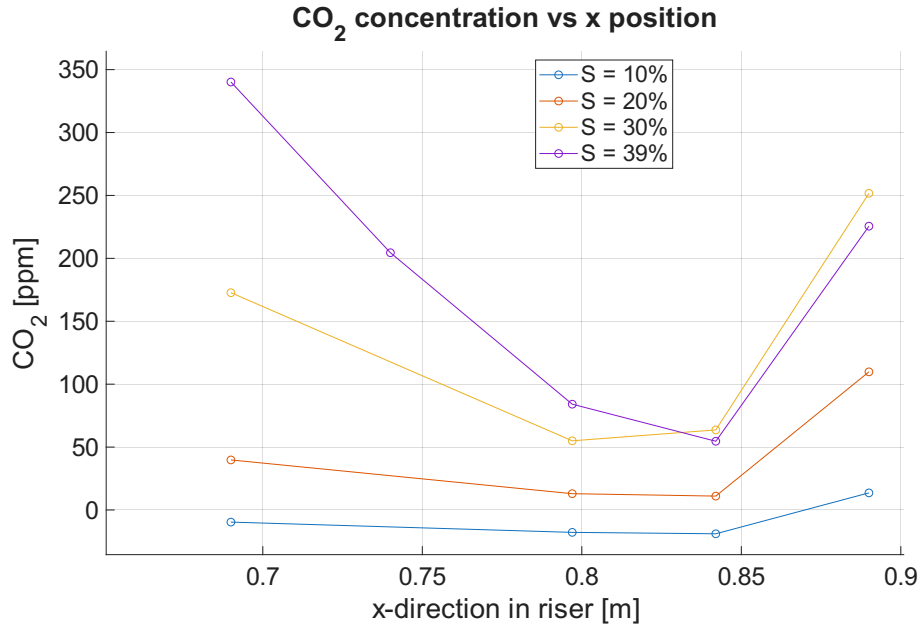


Figure 4.3: Distribution of CO_2 in row y250 for different proportions of secondary air. Blue, orange, yellow and red are 10%, 20%, 30% and 39% respectively.

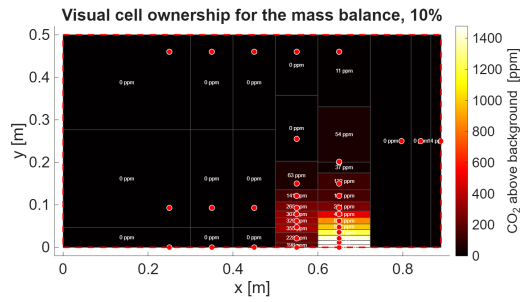
As mentioned in **Data Processing**, subsection 3.1.4, the CO_2 measurements were subjected to two different tests to ensure validity. Nearly all measurements for all cases passed the normal distribution tests and an example for how measurements were judged is shown in Figure B.1, available in *Appendix 2*. The amount of valid, uncertain and invalid tests can be found in Table B.1, also available in *Appendix 2*. Those that were invalid, (x650, y150) for **Case 20** and (x550, y200) for **Case 39** were disregarded. As neither of the points showed high peaks, their influence over results were assumed to be negligible. From the mass balance described in **Data Processing**, subsection 3.1.4, a detected/injected ratio of CO_2 is obtained as $\frac{CO_2 \text{ captured}}{CO_2 \text{ injected}}$. In Table 4.2, the different cases detected/injected ratio of CO_2 is shown as a percentage. The different experiments shown in Figure 4.4 were used to calculate the percentages in Table 4.2. These mass balance figures also show that cases with a higher proportion of secondary air seem to have a lower lateral dispersion in the x-direction.

Table 4.2 show that all proportions reach sufficiently high ratios of detected/injected CO_2 ($> 50\%$) and for that reason the results are considered trustworthy and viable. As mentioned previously, cases with a higher proportion of secondary air have a higher momentum of CO_2 , a lower perturbation of the primary air and a lower lateral dispersion to the sides. There is a trend of an increased ratio for higher proportions of secondary air. However, for **Case 39** ratio is not higher compared to that observed for **Case 30**. This could be because there is a difference in measurement points, where **Case 30** has a less refined grid which could have an effect on the percentage.

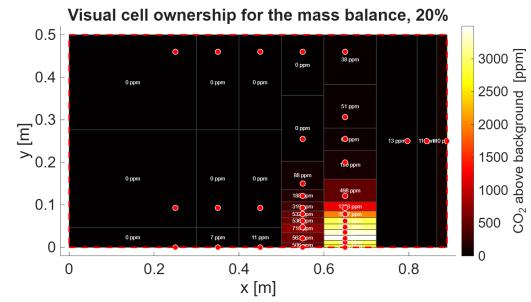
The mass balance is also presented as an intensity map in Figure 4.4. Although it is similar to Figure 4.2, it also considers the measurements taken from the side, row y250, and their contribution to the mass balance. Figure 4.4 has been included since it gives a better visualisation of the lateral dispersion in the x-direction of CO_2 compared to Figure 4.2. As shown in Figure 4.4, there is a trend of the relationship of concentrations between columns in the riser. A concentration bar is included next to the plots for respective cases where white indicates the highest concentrations and black the lowest. Similarly to Figure 4.2, the colour bar is normalized between cases meaning the lateral dispersion in the x-direction can be identified from the colour gradient. As seen in Figure 4.4 concentrations between the x650 and x550 column are closer for lower proportions rather than higher. This indicates that although penetration is stronger for higher proportions, the same is not true for lateral dispersion in the x-direction. However, it is worth considering that this thesis does not give a holistic view since CO_2 was only injected into one inlet of secondary, see **Future Research**, section 4.5.

Table 4.2: Detected/injected ratio of CO_2 for the different proportions of secondary air.

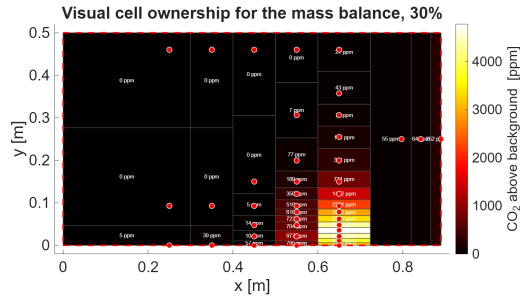
Case	Detected/injected [%]
10	52.0652
20	66.4387
30	70.3700
39	62.3247



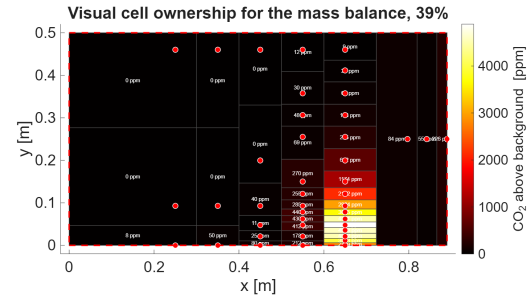
(a) Illustration of mass balance for Case 10.



(b) Illustration of mass balance for Case 20.



(c) Illustration of mass balance for Case 30.



(d) Illustration of mass balance for Case 39.

Figure 4.4: Illustration of mass balance for different proportions of secondary air.

4.2.1 Quantification of Penetration of Secondary Air

The goal of this subsection is to quantify the penetration and dispersion of CO_2 . As previously mentioned, the highest peaks for all cases were found in column x650, therefore the quantification will focus mostly on this specific column.

A parameter is created to quantify the penetration of the riser. The penetration depth, P_d , is defined based on where the peak concentration of CO_2 is found. It can be defined as both a distance and a percentage where 100% would correspond to a peak at 250 mm, the centre of the riser. One way to normalize the data and improve the reliability of results is to extract the mean penetration depth ($\overline{P_d}$). The $\overline{P_d}$ for each case was found by multiplying the distance with its corresponding concentration, and then summing the products. This sum was then divided by the sum of all measured concentrations for that specific case.

$$\frac{\sum y_i \cdot C_i}{\sum C_i} = \overline{P_{dj}} \quad (4.1)$$

Where y_i is the distance in the y-coordinate in i and C_i is the corresponding concentration of CO_2 in ppm. $\overline{P_{dj}}$ is the mean penetration depth for case j . The values used to calculate the mean penetration depth are shown in Figure B.2, available in *Appendix 2*.

In Table 4.3, penetration depth, mean penetration depth and both primary and secondary air velocity are given. u_{sec} is used to denote the velocity of the secondary air while u_{prim} is the velocity of the primary air.

Consistent with previous results, a higher proportion means a deeper penetration as seen from the P_d values in Table 4.3. This is both due to the increased momentum of CO_2 for higher proportions of secondary air and the decreased primary air velocity. The reduced primary air velocity means that there are less solids entrained, thus there is less resistance for the secondary air. The same trend was observed for the mean penetration depth.

Table 4.3: Primary and secondary air velocity, penetration depth and mean penetration depth for each case at x650.

Case	$u_{prim} \left[\frac{m}{s}\right]$	$u_{sec} \left[\frac{m}{s}\right]$	$P_d[\text{mm}]$	$P_d[\%]$	$\overline{P_d} [\text{mm}]$
10	0.63	3.12	12	4.8	39.29
20	0.56	6.24	21	8.4	45.56
30	0.49	9.36	36	14.4	50.93
39	0.43	12.16	48	19.2	57.30

The relationship between the penetration depth, mean penetration depth and secondary air velocity was considered interesting to investigate and is plotted in Figure 4.5. For the penetration depth based on concentration peaks, a linear relationship to the secondary air velocity is observed. This means that the penetration depth is not regulated by the total gas flow in the system but rather how its distributed. The linearity also indicates that the test matrix is well designed for separate mechanisms. For the mean penetration depth, the linearity of the relationship was maintained. However the difference between proportions is less extreme. Since the mean penetration depth maintains the linear relationship although all points in the x650 column are considered, the reliability of the results are strengthened.

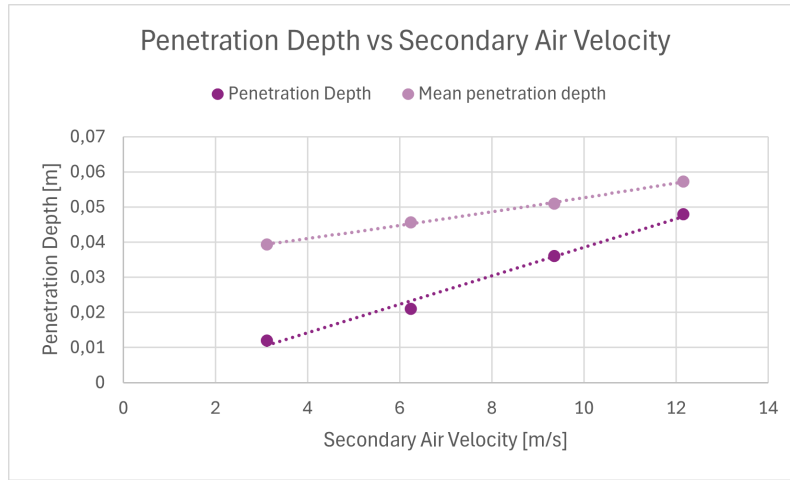


Figure 4.5: Plotting of secondary air velocity against penetration depth and mean penetration depth.

4.2.2 Quantification of Dispersion of Secondary Air

The mean and median of the CO_2 concentration in the y-direction were also compared for the different proportions of secondary air, these and their fraction are also listed in Table 4.4.

When calculating the mean and median, the measurements considered were those taken in column x650 for all cases. All cases except **Case 39** required that certain points be duplicated to make sure that the same number of points were considered for each case. The duplicates were created by taking the average of the point before and after. As previously mentioned, the point (x650, y150) for **Case 20** failed the normality test and was therefore disregarded. Instead, in the same way as for duplicates, the point was taken as the average of the point before and after, (x650, y125) and (x650, y200), respectively. Because there are an even number of points, 16, the median is calculated as the average of the two middle observations.

Both mean and median increase with the amount of secondary which is to be expected due to the larger concentrations of CO_2 . The middle points were located at (x650, y100) and (x650, y125) for **Case 10**, **Case 20** and **Case 30**. However, for **Case 39**, the middle points were located at (x650, y0) and (x650, y125), see Figure B.2 in *Appendix 2*. This irregularity is because for **Case 39**, the concentration in (x650, y100) is higher than the one in (x650, y0) due to the superior penetration.

Case 39 is also the exception in terms of the relationship between mean and median showcased in the sixth column of Table 4.3. All cases except **Case 39** maintains a higher mean than median. When $Mean \approx Median$, the dispersion of CO_2 can be considered rather symmetrical which means that peaks are more even and consequently lower values of CO_2 become more weighted which also indicates a more even dispersion. Therefore the results indicate that a higher proportion of secondary air gives a more symmetrical dispersion (in the y-direction). **Case 39** has a higher median compared to mean which means that the dispersion is left-skewed. Essentially this means that the majority of outliers are low values of CO_2 . Potentially, a proportion where $\frac{Median}{Mean} \approx 1$ would achieve a better dispersion.

Table 4.4: Mean, median and the relationship between the two for each case.

Case	Mean [ppm]	Median [ppm]	$\frac{Median}{Mean}$ [%]
10	536	209	38.93
20	1414	861	60.86
30	1976	1812	91.67
39	2265	2486	109.74

Data used to obtain the mean and median can be found in Figure B.2, available in *Appendix 2*.

Another way of describing the dispersion of CO_2 is to understand the distance between the peak concentration and at what point 50% of that concentration is reached. Figure 4.6 shows the dispersion of CO_2 along the y-direction in the riser for column x650. The dotted line, L_{50} shows where 50% of the peak concentration for the respective cases occur. At the bottom of the dotted lines, values for L_{50} are shown. However these values are the distance from the injection, hence Table 4.5 was constructed to extract the distance between the peak and 50% of the peak concentration ($D_{50} = L_{50} - P_d$). Consistent with the previous results, a higher proportion of secondary gives a more disperse CO_2 profile in the y-direction, except for **Case 30** which has the lowest value. This is likely because the concentration peak in **Case 30** is high, close to the peak for **Case 39**. Concentrations then plummet for **Case 30** which is why this lack of dispersion could not be seen from the comparison of mean and median in Table 4.3.

Two points stand out in Figure 4.6, the (x650, y0) and (x650, y38) points for **Case 39**. For all other points, concentrations of CO_2 increases with percentage of secondary air. However, in these two points, **Case 30** shows higher values than **Case 39**. This could be because of two different reasons. Since the peak is found further in for **Case 39**, it could be that this elongation of the peak causes this phenomenon. Another reason could be that for **Case 39** a more efficient penetration of the back-mixing layer means that CO_2 is no longer trapped at the same rate as for the lower proportions. Fully understanding this with acquired results from this thesis is difficult and requires more research, see **Future Research**, section 4.5.

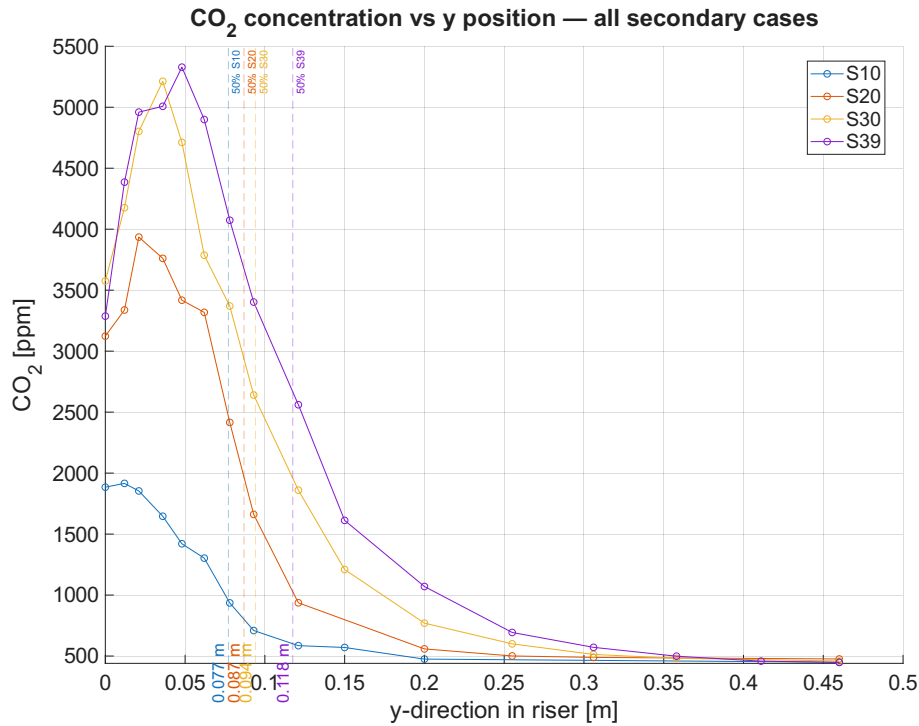


Figure 4.6: Illustration of the dispersion along the y-axis and at what point D_{50} is reached for all cases. **Case 39**=purple, **Case 30**=yellow, **Case 20**=orange and **Case 10**=blue.

Table 4.5: Measurement in the y-direction where 50% of CO_2 concentration is achieved for all cases.

Case	P_d [mm]	L_{50} [mm]	D_{50} [mm]
10	12	77	65
20	21	87	66
30	36	94	58
39	48	118	70

Figure 4.6 can be difficult to analyse since the difference in concentration between cases is large. Therefore a normalized version was created, Figure 4.7. For all cases, each concentration measurement was divided by the sum of all concentrations for the respective case to obtain a percentage.

This clarifies the behaviour of CO_2 between cases. Consistently with other results, for higher proportions of secondary air the peaks moves further inside the riser. An interesting observation is that **Case 20** and **Case 30** have narrow peaks. In comparison, **Case 39** shows a broader peak, or dispersion. This was discussed below Table 4.3 but Figure 4.7 visualizes this behaviour clearly. Interestingly, the peak for **Case 10** is also more broad even though it has the lowest $\frac{Mean}{Median}$ percentage.

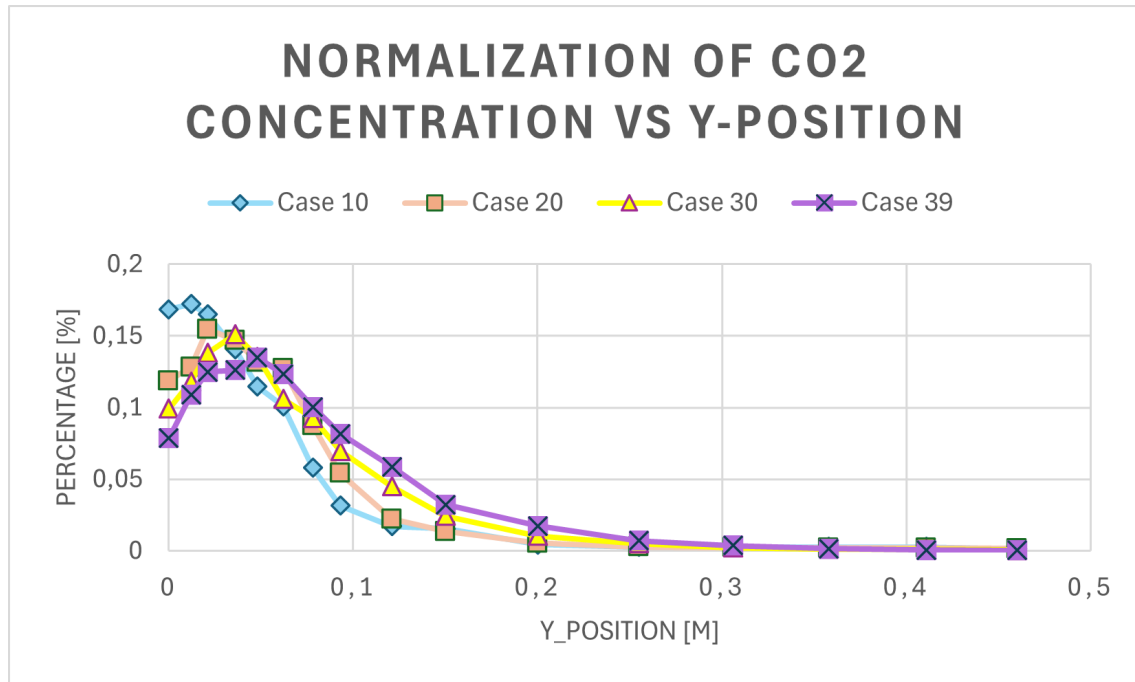


Figure 4.7: Normalized version of Figure 4.6. The y-axis shows the percentage of CO_2 concentrations and x is the depth of the riser (y-direction).

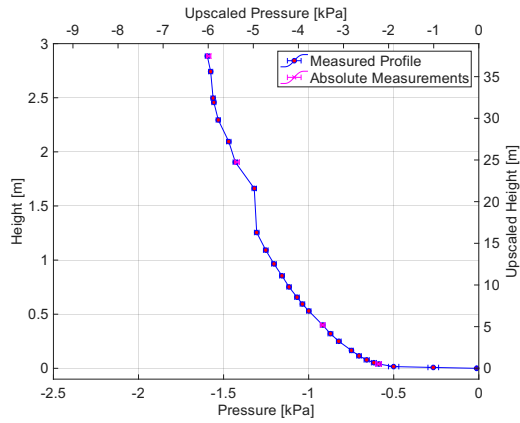
4.3 Vertical Distribution of Solids

In this section results regarding the vertical distribution of solids is investigated. Since **Case 0** utilized no secondary air it was not discussed in the previous section. When studying the movement of solids, **Case 0** was used as a reference. For all cases, pressure profiles were obtained which are shown in Figure 4.8. At the bottom region, all cases show similar behaviour. The low slope observed at the far right of the pressure-drop profile for all cases indicates a region with a high solids holdup. This suggests that a dense bed is formed in the lower part of the furnace in all operating conditions. In addition, higher proportions of secondary lead to a higher pressure drop and a higher dense bed. The pressure graphs also show that when secondary air is introduced a more distinct breaking point forms when the graph goes from the splashing to the transport zone. This is likely due to that increased secondary air hinders entrainment thus fewer particles reach the upper parts of the riser.

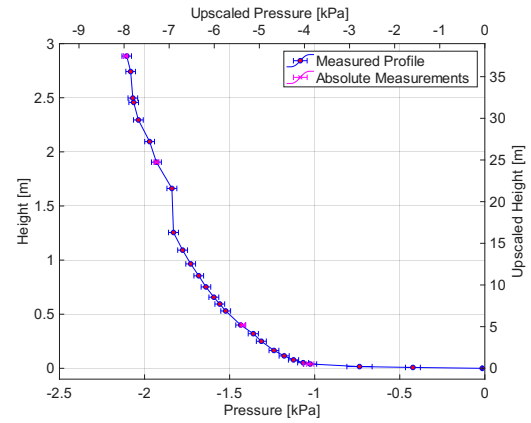
Because the pressure fluctuates during operation, error bars are displayed to show the magnitude of fluctuations which are shown in Figure 4.8. It can be observed that these fluctuations increase with proportions of secondary except for **Case 20** and **Case 30**. However, the differences between the two is small and for this reason considered negligible. Increased fluctuations show that there is more flow irregularity which is likely also due to an increased gas and solids mixing. In **Quantification of Dispersion of Secondary Air**, subsection 4.2.2, it is shown that an increased secondary air proportion most times achieves a higher dispersion into the riser. These results are consistent with the increased fluctuations observed for the pressure profiles that also indicate an improved gas/solids mixing. It is however worth mentioning that all transducers should have fluctuations which is not the case for lowest points for **Case 0** and **Case 10**. This suggests that the lowest pressure transducer were clogged during these tests.

As mentioned throughout this thesis the comparison to industrial boilers is important. Therefore, the equations in subsection 3.1.3 were utilized to create the scaled axes in Figure 4.8. These scaled axes are shown on the right and upper part of said figure.

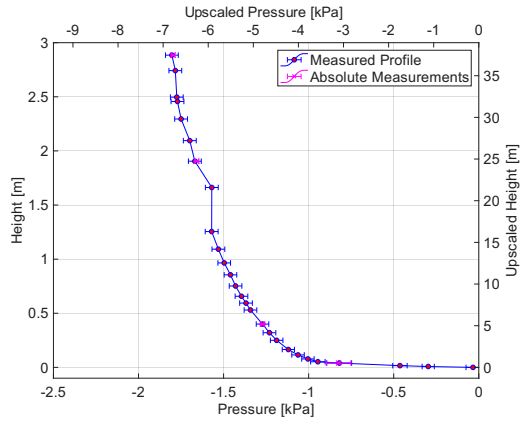
4. Results and Discussion



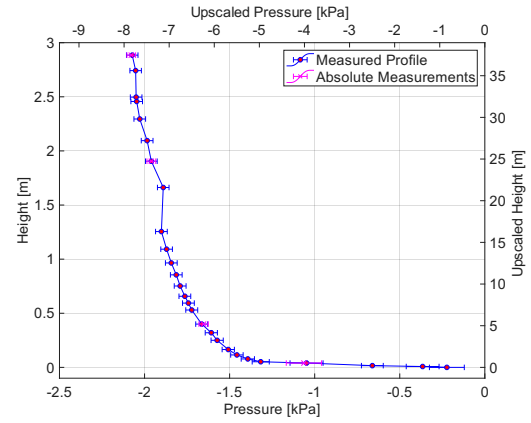
(a) Obtained pressure profile for **Case 0**.



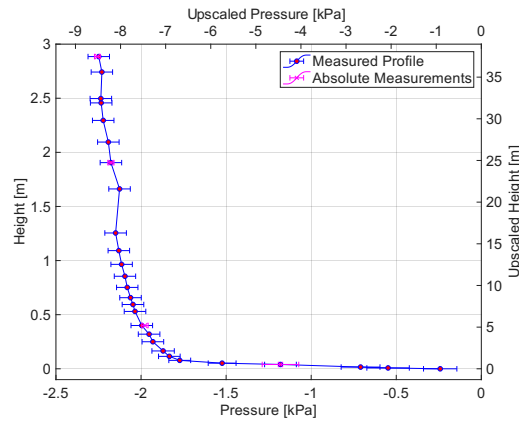
(b) Obtained pressure profile for **Case 10**.



(c) Obtained pressure profile for **Case 20**.



(d) Obtained pressure profile for **Case 30**.



(e) Obtained pressure profile for **Case 39**.

Figure 4.8: Pressure profiles for different proportions of secondary air. The values for S13 are on the left and bottom axes and the upscaled values are found on the top and right axes.

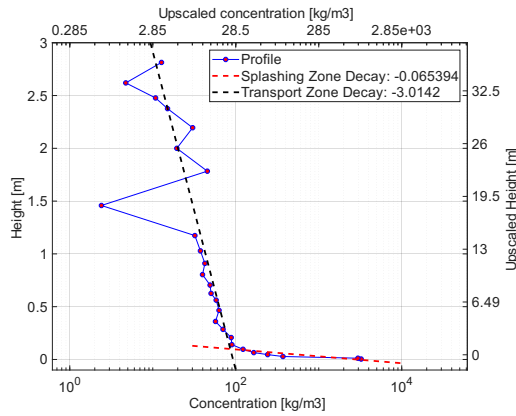
As described in **Data Processing**, subsection 3.1.4, concentration profiles were computed from the acquired pressure profiles. The concentration graphs for all proportions of secondary air are shown in Figure 4.9. This gives a more clear depiction of the distribution of solids along the riser and both the splashing (a) and transport (K) zone decay coefficients are given, Table 4.6.

For **Case 0** and **Case 10** in Figure 4.9, an outlier can be observed at the unscaled height of 1.46 m. This outlier originates from an error in the pressure transducer located at 1.662 m, see Figure 4.8. This faulty measurement results in an almost vertical section of the pressure profile, producing a small pressure drop and consequently a low concentration. As determining which data points to include in the calculation of decay coefficients is inherently difficult and can significantly affect the resulting values, points were assigned to the splashing and transport zones visually. For all cases, the seven lowest concentration points were considered to belong to the splashing zone while the remaining points were assigned to the transport zone. Since several outliers were present in the transport zone, data points falling outside a ± 1 standard deviation interval were excluded. However, for all cases containing secondary air, this criterion proved too restrictive and the interval was expanded to ± 1.5 standard deviations. Consequently, the outlier described above was excluded from the decay coefficient calculations. For **Case 30** and **Case 39**, the decay coefficients were considered unreasonable when all transport-zone points were included. Because of this, the line was prioritized to follow the lower points in the riser as these are typically more trustworthy. Thus the top points were not considered when calculating the decay coefficients for these cases.

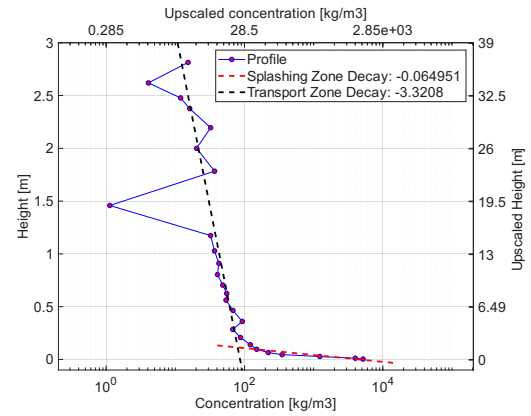
The dense bed region is more visible in Figure 4.9 compared to Figure 4.8. Higher proportions of secondary air, **Case 30** and **Case 39**, strongly incentivize a dense bed. This can be seen from the agglomeration of points at the far right of the graph for 4.9d and 4.9e. These agglomerated points can be an indication of the vertically linear region from the decay coefficient of the dense bed [4]. However this region is not represented in the graphs shown in Figure 4.9. Maintaining a higher proportion of secondary air is therefore considered to be helpful in aiding a well defined dense bed, splashing and transport zone.

Decay coefficients for the splashing and transport zone are listed in Table 4.6. For all cases except **Case 0**, the transport decay coefficient increases. This is to be expected since the higher proportions of secondary air have lower entrainment and more rapid solids decay [4]. The splashing zone decay coefficient is more unpredictable where **Case 10** in addition to **Case 0** show higher values than those observed for remaining cases. **Case 20**, **Case 30** and **Case 39** do show the expected trend of increasing transport decay coefficient. Once again, the increase is expected as the dense bed increases with increased secondary air which means that there are less solids present in the splashing zone. As mentioned in **Data Processing**, subsection 3.1.4, obtaining a reliable value for the decay coefficients is difficult. Same as for the pressure profiles, concentrations were scaled. These are once again found on the right and upper axis.

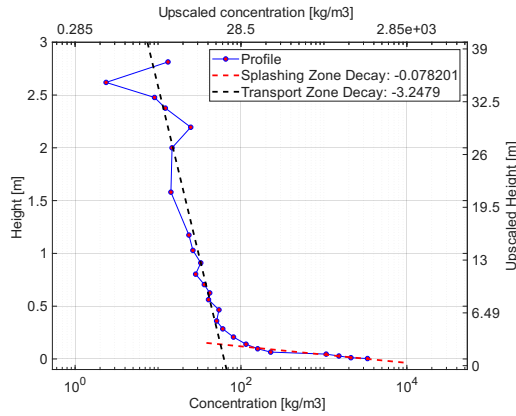
4. Results and Discussion



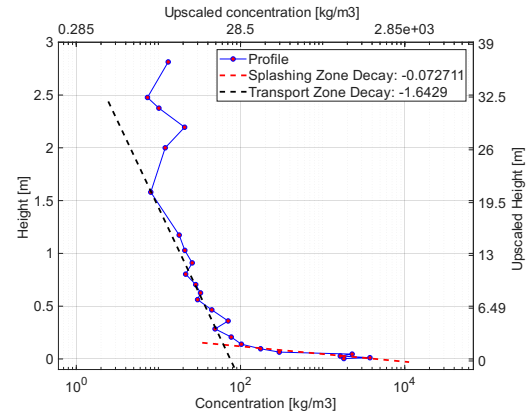
(a) Obtained concentration profile for Case 0.



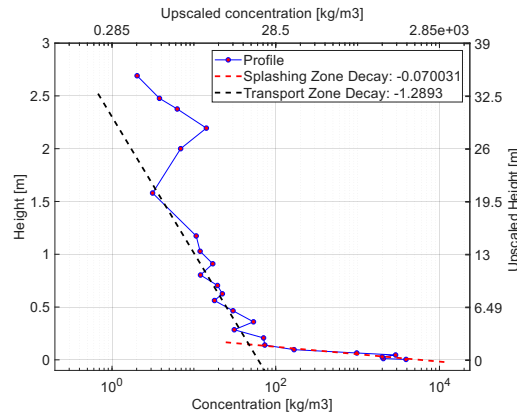
(b) Obtained concentration profile for Case 10.



(c) Obtained concentration profile for Case 20.



(d) Obtained concentration profile for Case 30.



(e) Obtained concentration profile for Case 39.

Figure 4.9: Concentration profiles for different proportions of secondary air. The values for S13 are on the left and bottom axes and the upscaled values are found on the top and right axes.

Table 4.6: Decay coefficients for the splashing and transport zone.

Case	K	a
0	-3.0142	-0.065394
10	-3.3208	-0.064951
20	-3.2479	-0.078201
30	-1.6429	-0.072711
39	-1.2893	-0.07003

To further evaluate the solids flow, circulation rates for all cases were obtained, see Table 4.7. It was found that a higher proportion of secondary air yields a lower circulation rate. One reason for this is that the higher proportions of secondary air have lower primary air velocities and consequently lower entrainment from the dense bed. Another reason is that the secondary air itself decreases the entrainment of solids, which is in agreement with findings in Djerf's dissertation [4].

An upscaled version of the circulation rate can also be obtained once again using the Table 2.2. The calculations are shown in Equation 3.8 available in **Scaling**, subsection 3.1.3.

Table 4.7: Averaged and their scaled counterparts of circulation rate for the different proportions of secondary air.

Case	$G_s \left[\frac{\text{kg}}{\text{s m}^2} \right]$	Scaled $G_s \left[\frac{\text{kg}}{\text{s m}^2} \right]$
0	4.76506	4.944107
10	4.51118	4.680689
20	4.09392	4.247749
30	3.93682	4.084746
39	3.05134	3.165994

In Figure 4.10, the five circulation rates for each case are plotted. If the distances between tests are small, it indicates trustworthy results. There is one small outlier for **Case 39**. One possible explanation is the concept of slugging discussed in **Fluidization in CFB boilers**, section 2.3. Since slugging occurs for lower velocities, slugging may become more pronounced at higher secondary-air fractions for the butterfly-valve. The decrease in circulation rate between cases is irregular with a large gap between **Case 30** and **Case 39**.

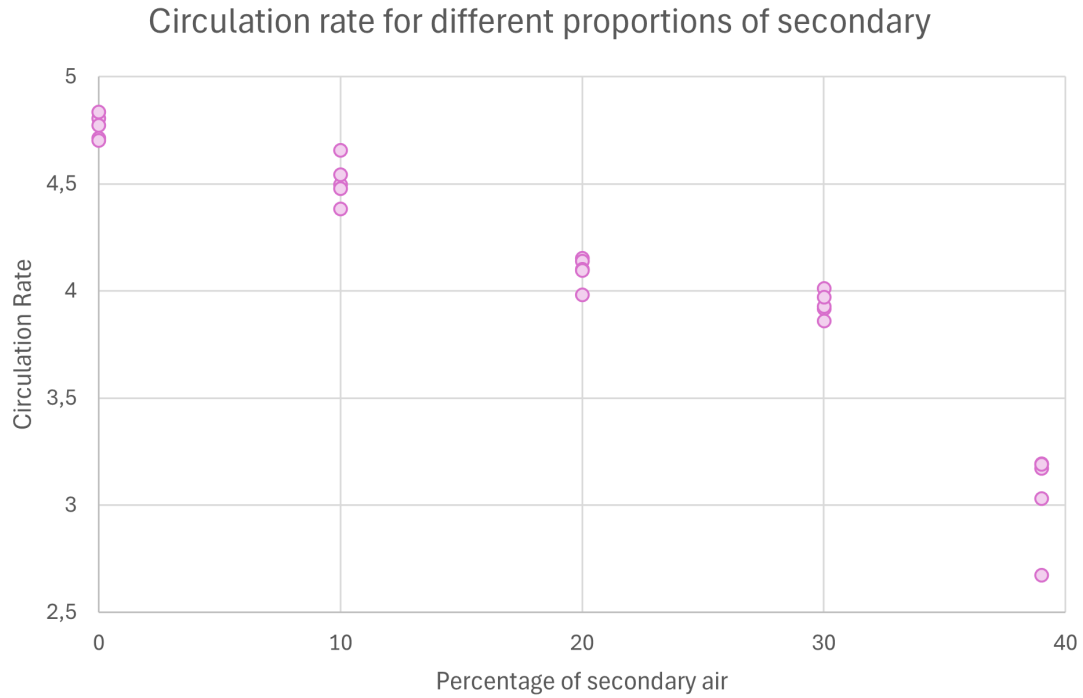


Figure 4.10: Circulation rates between cases and their distribution.

4.4 Comments on Scaling

Two of the scaled parameters were compared to values provided by Amagerværket, concentrations and circulation rate. The dimensions of Amagerværket's riser are 40x20x10 [m] for height, width and depth respectively. For S13's dimensions see **Experimental Setup**, section 3.1.

Scaled concentrations showed relatively similar results to those obtained from Amagerværket. As mentioned previously, industrial boilers typically have a lot less transducers compared to S13. Amagerværket has eight transducers at different heights of the riser, one at 3 m, one at 4 m, two at 12.7 m, two at 17.2 m and two at 26.6 m. From the pressure drop for these points concentrations can be calculated for 3.5, 8.4, 15 and 22 m. As there exist no concentrations for exactly these points for the upscaled S13 model, the closest ones to them were used, 3.7, 8.1, 15.2 and 20.5 m. Additionally, a circulation rate comparison was made possible thanks to Chalmers fluidization group. The circulation rate calculated for Amagerværket considers some assumptions. All solids that exist at the height corresponding to the cyclone duct are expected to move into it. That neglects the back-mixing at the cyclone height. Assumptions made when calculating S13's circulation rate are discussed in **Circulation Rate**, subsubsection 3.1.1.3.

S13's scaled concentrations and circulation rates and their counterparts in Amagerværket are shown in Table 4.8. $C_{i/j}$ are used to denote concentrations at height position i for S13 and height position j for Amagerværket. **HOFOR** tends to operate their boiler with $\approx 50\%$ secondary air which is why **Case 39** was used as a comparison.

Table 4.8: Comparison of scaled pressures and concentrations between **Case 39** and Amagerværket.

$C_{i,j}$	Case 39 _{scaled}	Amagerværket
$C_{3.7/3.5}[\frac{kg}{m^3}]$	9.1	23
$C_{8.1/8.4}[\frac{kg}{m^3}]$	6	3.5
$C_{15.2/15}[\frac{kg}{m^3}]$	3.1	1.9
$C_{20.5/22}[\frac{kg}{m^3}]$	0.9	1.6
G_s	3.17	2.9

Concentrations (aside from $C_{3.7/3.5}$) and circulation rate along the riser are relatively similar between the model and Amagerværket. It is worth mentioning that Amagerværket's pressure and concentrations vary severely throughout the year (and the data used here is taken as representative conditions) but the scaled S13 concentrations are in the same magnitude as those observed by **HOFOR** which is an indication of representative results for the latter. Some discrepancies may also arise from the limitations of S13 discussed in **Experimental Setup**, section 3.1.

4.5 Future research purposes

A few different ideas were contemplated during this thesis and they are presented here under this section.

The unexpected movement of CO_2 towards the right side of the riser needs to be investigated. This could be helpful in providing clarity as to why this is occurring and potentially enable the observing of higher peaks than those observed in this thesis.

One of the limitations of the selected velocity of $0.7 \frac{m}{s}$ for S13 is that it is not representative of industrial boiler velocities which are closer to $\sim 4 \frac{m}{s}$ which would correspond to a velocity of $1.1 \frac{m}{s}$ for S13. Upgrading the S13 unit so that it is able to operate at industrially representative velocities while simultaneously achieving significant proportions of secondary air would be ideal.

As shown in Figure 4.1, there are several different cases that can be tested. It would be interesting to compare the same proportion of secondary between different velocities at the top of the boiler. For example comparing 20% secondary for velocities of 0.6, 0.7 and $1.1 \frac{m}{s}$. Alternatively, the same flow of secondary could be

compared for different velocities. Higher proportions of secondary, for example 50%, would also be interesting to study. Currently, S13 is unable to achieve these high proportions due to safety reasons but as a future research subject it is interesting.

Trying different points of injection would also be interesting. Moving the injection point to the left could potentially help locate the maximum peak. Moving between levels of secondary would also be interesting in the aim of understanding the movement of secondary air.

Implementing CO_2 injection in more secondary air inlets is another alternative. This could also help in understanding if the decreased lateral dispersion of CO_2 in the x-direction for higher proportions of secondary air has any significant effect.

5

Conclusion

In this study, results were concluded regarding secondary air jet penetration for a constant velocity of $0.7 \frac{m}{s}$ at the top of a cold-flow model. Five cases of different proportions of secondary air were studied. CO_2 maps indicated a longer and more dispersed (in depth, y-direction) penetration of secondary air for higher proportions. The CO_2 gas tended to move towards the right side of the riser for all cases, potentially due to the effect of the gas-solids flow recirculated from the loop seal or to local defluidization.

Mass balances regarding the detected/injected ratio of CO_2 showed meaningful results for all proportions of secondary air. However, an unexpected decrease in this ratio for 39% of secondary air was observed. The illustration of mass balances also provided valuable information regarding the lateral dispersion (x-direction) of CO_2 . Although a higher proportion of secondary air indeed achieves a higher penetration, dispersion in the x-direction decreases.

Graphs were also created to visually describe the dispersion of CO_2 along the depth of the riser for column $x=650$ mm. A deeper dispersion for 39% of secondary air was once again observed for the normalized version of the graph. Mean, median and the fraction between the two were evaluated for all four cases containing secondary air. The relationship between the mean and median was especially interesting for the purpose of describing the dispersion of CO_2 in the y-direction. Mean and median moved closer in values for higher proportions of secondary air, indicating a more even depth dispersion.

From the side of the riser, concentrations were elevated near the wall ($x=890$ mm, $y=250$ mm) before decreasing and then eventually increasing again. The high concentration near the wall was considered to exist either due to entrapment of CO_2 from the back-mixing layer or from the gas moving in conjunction with the solids causing CO_2 to travel back down together with the back-mixing. This increased CO_2 near the wall was unexpected and requires additional research.

According to the solids concentration profiles, more defined dense beds were observed for the higher proportions of secondary air. Splashing and transport zone decay coefficients were obtained for all cases, including the reference without secondary air that had not been considered for the distribution of gas. For all cases except the reference, the splashing decay coefficient increased with higher proportions of secondary air, which was to be expected as the dense bed height increases. This means that less solids exist in the splashing zone. The reference case and the case for 10% secondary air deviated from the trend that the transport decay coefficient increases with higher proportions. An increase was expected as higher proportions of secondary air have lower entrainment which causes less amount of solids to exist in the transport zone.

Solids circulation rate for all cases decreased with increasing proportions of secondary air, which is consistent with previous studies.

Pressure, concentration, decay coefficients and circulation rate were all scaled. Scaled concentrations and solids circulation rates were shown to have similar values to their counterparts in Amagerværket, **HOFOR**'s CFB boiler in Copenhagen.

In conclusion, this study has shown that a higher proportion of secondary air is beneficial for penetration and dispersion (in depth) for CFB boilers. Lateral dispersion towards the sides was found to decrease for increasing proportions of secondary air. It also confirms the prior notion that an increased proportion of secondary air results in a lower external circulation of solids. Applying a higher proportion of secondary air could help aid in the penetration of fuel and subsequent combustion. The authors therefore suggest operation with higher proportions of secondary air if the goal is a deeper and more disperse depth penetration. However, it is also worth considering that increased secondary air proportion means a lower lateral dispersion (in the x-direction) and lesser circulation.

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A

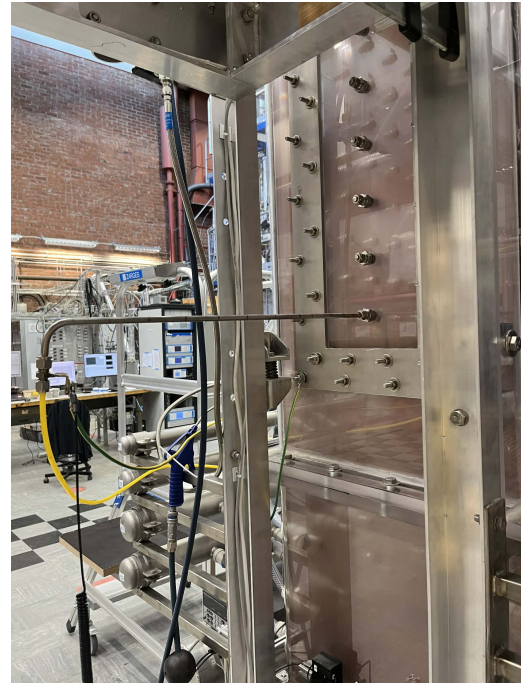
Appendix 1, Equipment and Setup



Figure A.1: Perforated nozzles that provide primary air in Amagerværket, provided by HOFOR.



(a) Measuring points used for the CO_2 mapping.



(b) Measurements obtained with a constant y of 250 mm.

Figure A.2: All available CO_2 measuring ports for S13.



(a) S13 cyclone.



(b) Abrasion caused by cyclone.

Figure A.3: Limitations of S13.



Figure A.4: Point of injection with added plug for reduction of cross-sectional area.



Figure A.5: The CO_2 measuring probe with markings at 0, 12, 21, 36, 48, 62, 78, 93, 121, 150, 200, 255, 306, 358, 411 and 460 mm.



(a) Circulation valve at the loop seal.



(b) Exit of cyclone with schematic picture of the butterfly-valve operation.

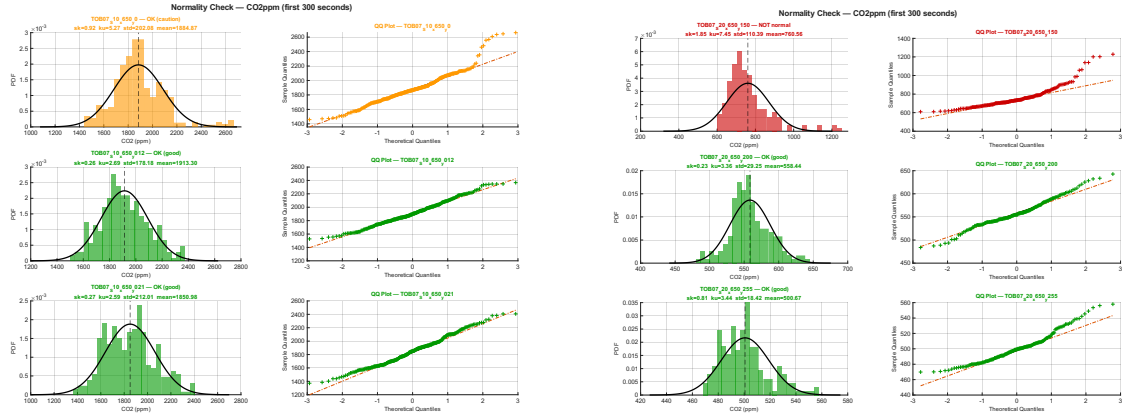
Figure A.6: Circulation rate equipment.

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B

Appendix 2, Equations and Results

$$\Delta P = (\rho_s(1 - \varepsilon_g) + \rho_g \cdot \varepsilon_g)g \cdot \Delta h \quad (\text{B.1})$$



(a) Illustration of tests that are normally distributed and therefore "Valid" (=green) and plots that are almost normally distributed, hence "Uncertain" (=yellow). The QQ-plots for respective test is shown on the right of the distribution plots.

(b) Illustration of tests that are normally distributed and therefore "Valid" (=green) and plots that are not normally distributed, hence "Invalid" (=red). The QQ-plots for respective test is shown on the right of the distribution plots.

Figure B.1: Normal distribution plots with their respective QQ-plots on the right.

Table B.1: Number of valid, uncertain and invalid tests for respective cases.

	Number of Valid tests	Number of Uncertain tests	Number of Invalid tests
Case 10	26	6	0
Case 20	27	5	1
Case 30	29	6	0
Case 39	28	12	1

x=650	Case 10	Case 20	Case 30	Case 39
0	1445,81	2684,81	3136,81	2848,81
12	1476,81	2898,81	3736,81	3946,81
21	1414,81	3496,81	4362,81	4520,81
36	1207,81	3321,81	4773,81	4568,81
48	982,809	2979,81	4272,81	4889,81
62	864,809	2879,81	3348,81	4461,81
78	497,809	1976,81	2931,81	3634,81
93	270,809	1222,81	2201,81	2963,81
121	146,809	498,809	1421,81	2122,81
150	131,809	309,309	770,809	1173,81
200	36,8085	119,809	331,809	631,809
255	23,8085	62,8085	161,809	254,809
306	23,8085	50,8085	74,8085	132,809
358	23,8085	44,3085	42,8085	60,8085
411	23,8085	44,3085	31,8085	19,8085
460	10,8085	37,8085	20,8085	9,8085
Mean	536,434	1414,34	1976,37	2265,12
Median	208,809	860,809	1811,81	2485,81
Median/Mean	0,38925	0,60863	0,91674	1,09743
Total	8582,94	22629,4	31621,9	36241,9
Mean Pen	0,03929	0,04556	0,05093	0,0573
Pen	0,012	0,021	0,036	0,048
vsec	3,12	6,24	9,36	12,16
Ambient CO2	438,192			

Figure B.2: Concentrations in ppm for x=650 for all cases that were used to calculate mean, median and median penetration depth. Middlepoints, used for the calculation of the median, are highlighted in pink. The cell marked in red for **Case 20**, (x650, y150), is taken as the average between the 125 and 200 mm point since the actual point failed the normal distribution test. Points marked in yellow are duplicates that were created so that all cases have the same amount of points. These were also calculated by taking the average of the point before and after. From these measurements the ambient concentration of CO_2 , 438.1915, was subtracted.

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